Chapter 7

The Second Law Of Thermodynamics

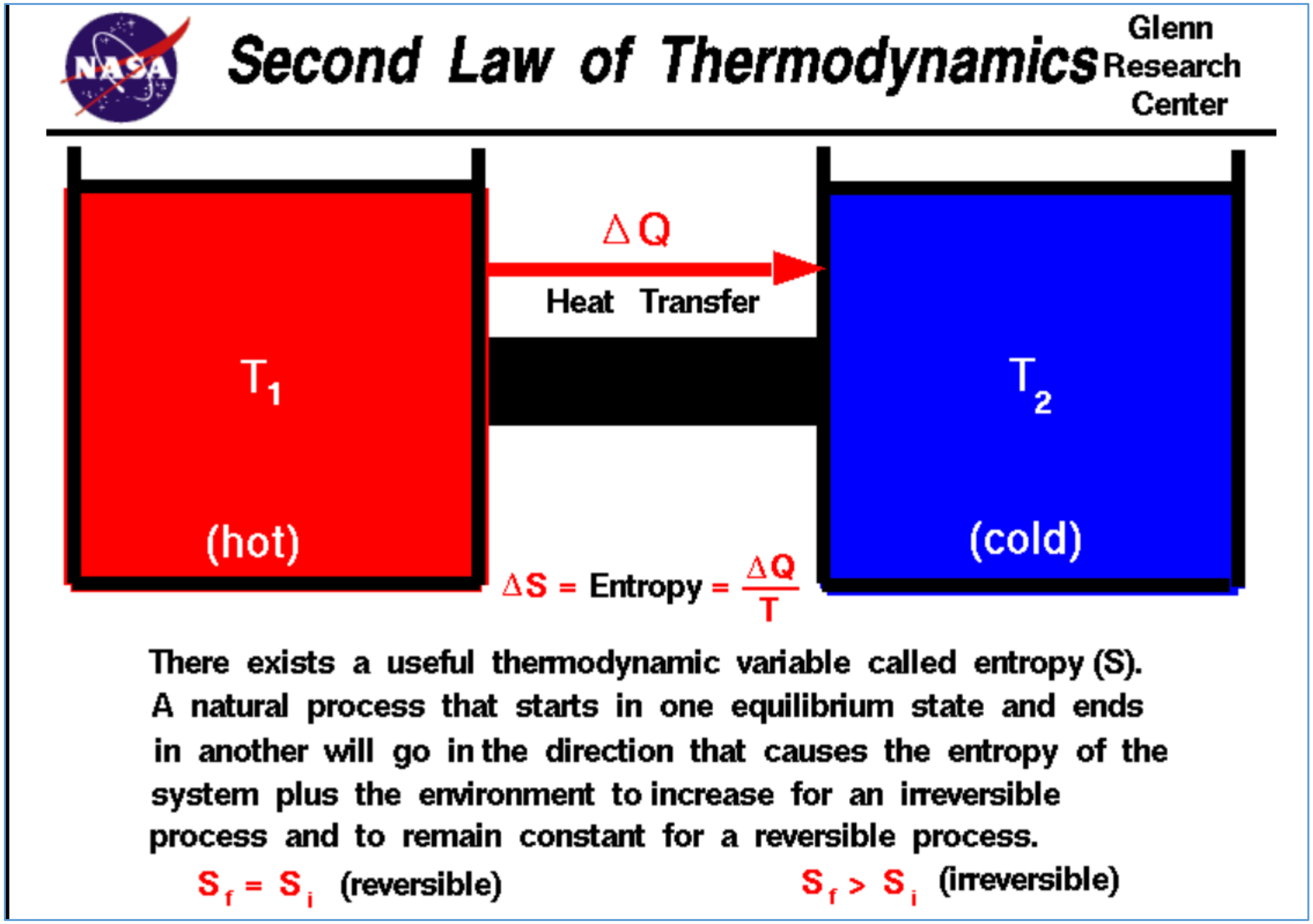
Objectives

- Introduce the second law of thermodynamics.
- Identify valid processes as those that satisfy both the first and second laws of thermodynamics.
- Discuss thermal energy reservoirs, reversible and irreversible processes, heat engines, refrigerators, and heat pumps.
- Describe the Kelvin–Planck and Clausius statements of the second law of thermodynamics.
- Apply the second law of thermodynamics to cycles and cyclic devices.

Objectives

- Apply the second law to develop the absolute thermodynamic temperature scale.
- Describe the Carnot cycle.
- Examine the Carnot principles, idealized Carnot heat engines, refrigerators, and heat pumps.
- Determine the expressions for the thermal efficiencies and coefficients of performance for reversible heat engines, heat pumps, and refrigerators.

The second law stipulates that the total entropy of a system plus its environment can not decrease; it can remain constant for a **reversible** process but must always increase for an **irreversible** process



The first law of thermodynamics asserts that energy must be conserved in any process involving the exchange of heat and work between a system and its surroundings.

1-3 HEAT TRANSFER-1

***The** first law requires that the rate of energy transfer into a system be equal to the rate of increase of the energy of that system.*

The second law requires that heat be transferred in the direction of decreasing temperature.

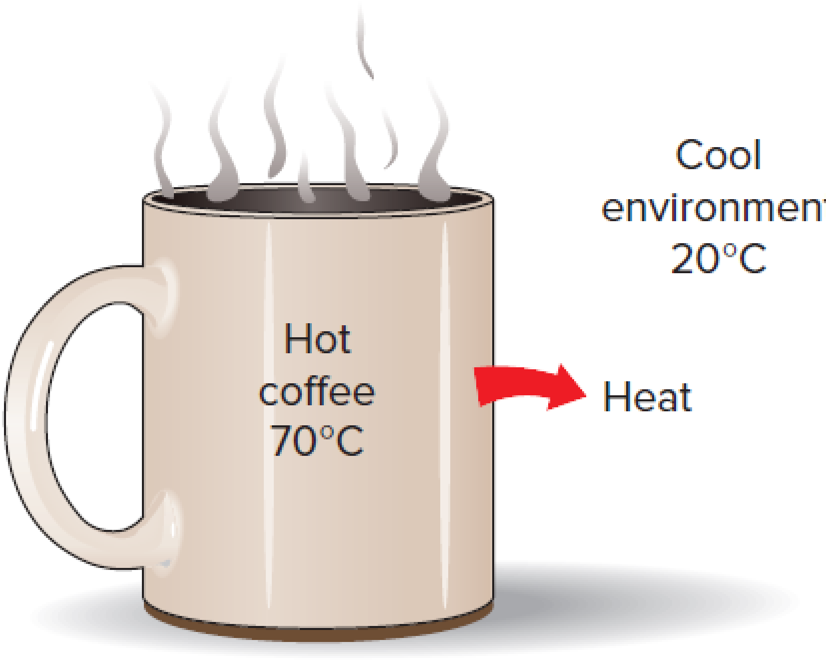


FIGURE 1–6
Heat flows in the direction of decreasing temperature.

Now let us consider the reverse process—the hot coffee getting even hotter in a cooler room as a result of heat transfer from the room air. We all know that this process never takes place. Yet, doing so would not violate the first law as long as the amount of energy lost by the air is equal to the amount gained by the coffee.

7-1 INTRODUCTION TO THE SECOND LAW

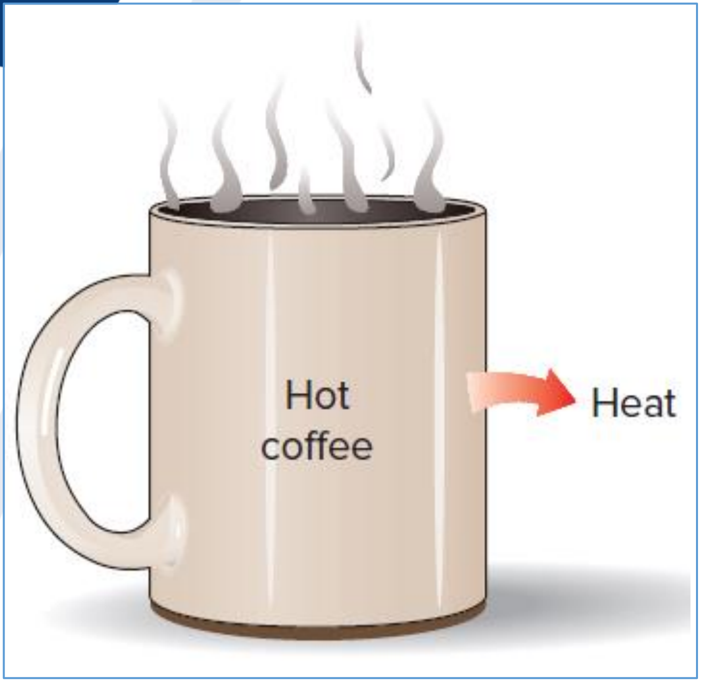


FIGURE 7-1

A cup of hot coffee does not get hotter in a cooler room.

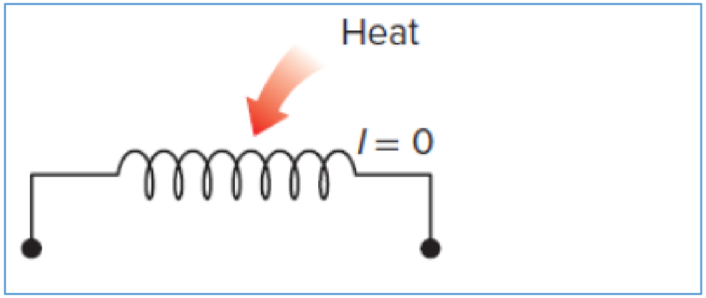


FIGURE 7-2

Transferring heat to a wire will not generate electricity.

These processes cannot occur even though they are not in violation of the first law.

7-1 INTRODUCTION TO THE SECOND LAW-1

MAJOR USES OF THE SECOND LAW

1. The second law may be used to identify the direction of processes.
2. The second law also asserts that energy has *quality* as well as quantity. The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to its quality.
3. The second law of thermodynamics is also used in determining the *theoretical limits* for the performance of commonly used engineering systems.
4. such as heat engines and refrigerators, as well as predicting the *degree of completion* of chemical reactions.

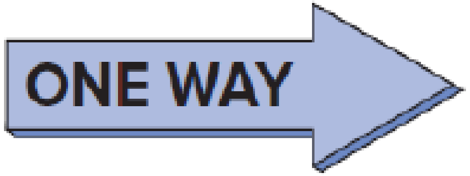


FIGURE 7-4

Process occur in a certain direction, and not in the reverse direction.

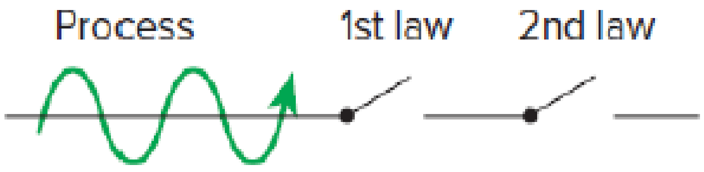


FIGURE 7-5

A process must satisfy both the first and second laws of thermodynamics to proceed.

7-2 THERMAL ENERGY RESERVOIRS

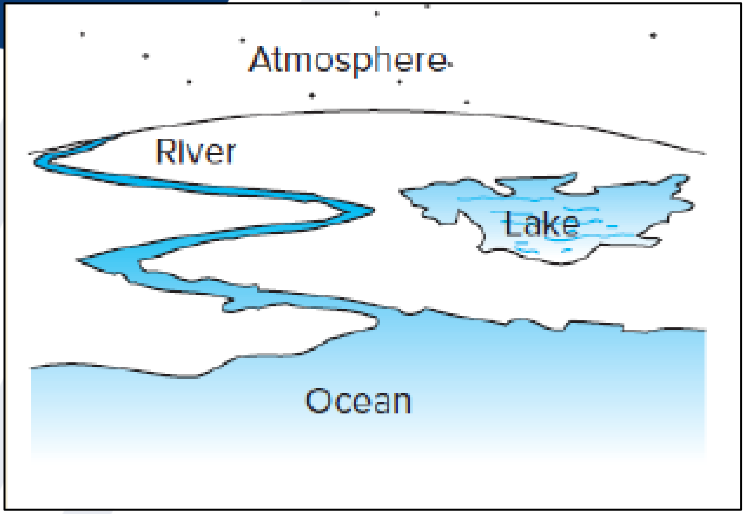


FIGURE 7-6

Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs.

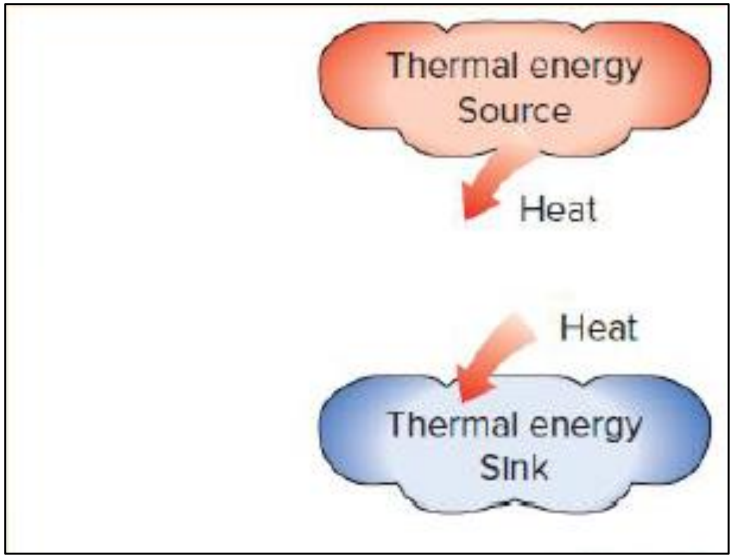


FIGURE 7-7

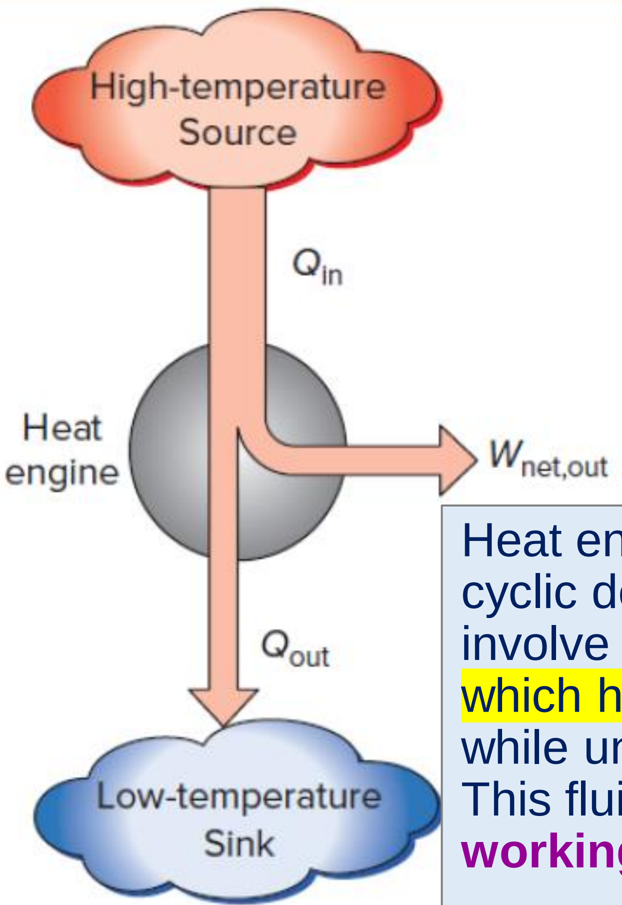
A source supplies energy in the form of heat, and a sink absorbs it.

- A hypothetical body with a relatively large *thermal energy capacity* (mass x specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature is called a **thermal energy reservoir, or just a reservoir.**
- **In practice, large bodies of water such as oceans, lakes, and rivers as well as the atmospheric air can be modeled accurately as thermal energy reservoirs because of their large thermal energy storage capabilities or thermal masses.**

7-3 HEAT ENGINES

HEAT ENGINES: The devices that convert heat to work.

1. They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).
2. They convert part of this heat to work (usually in the form of a rotating shaft.)
3. They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).
4. They operate on a cycle.



Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the **working fluid.**

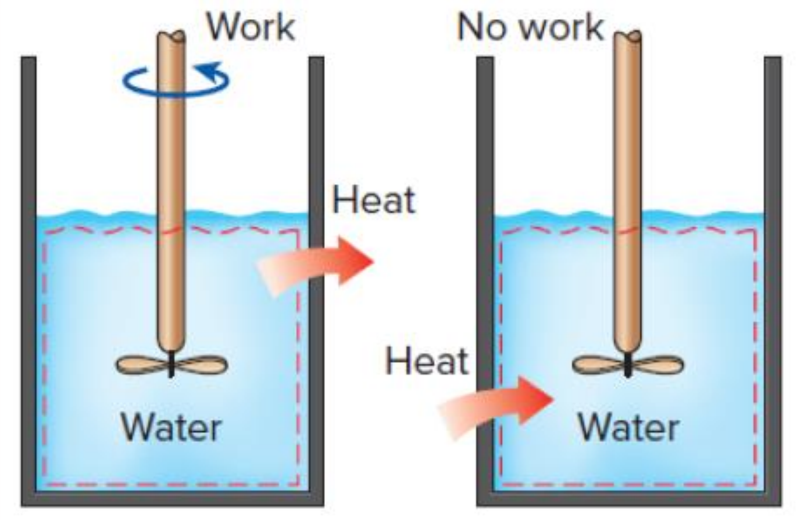


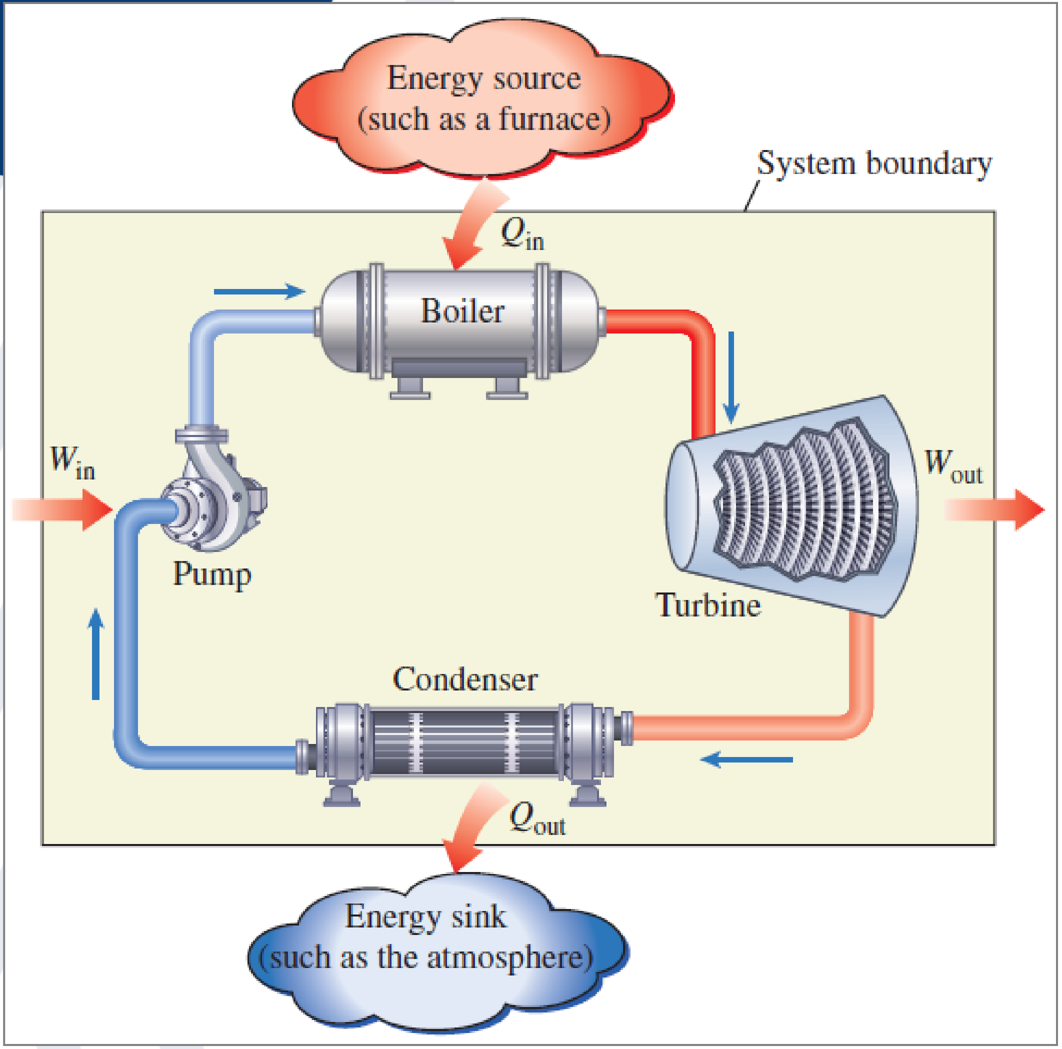
FIGURE 7-9

Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

FIGURE 7-8

Work can always be converted to heat directly and completely, but the reverse is not true.

A steam power plant



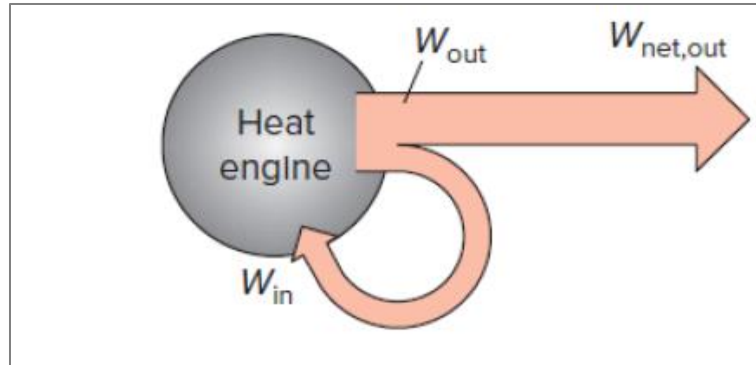


FIGURE 7-11

A portion of the work output of a heat engine is consumed internally to maintain continuous operation.

$$W_{net,out} = W_{out} - W_{in} \qquad (kJ)$$

$$W_{net,out} = Q_{in} - Q_{out} \qquad (kJ)$$

Q_{in} = amount of heat supplied to steam in boiler from a high-temperature source (furnace)

Q_{out} = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)

W_{out} = amount of work delivered by steam as it expands in turbine

W_{in} = amount of work required to compress water to boiler pressure

Thermal efficiency

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

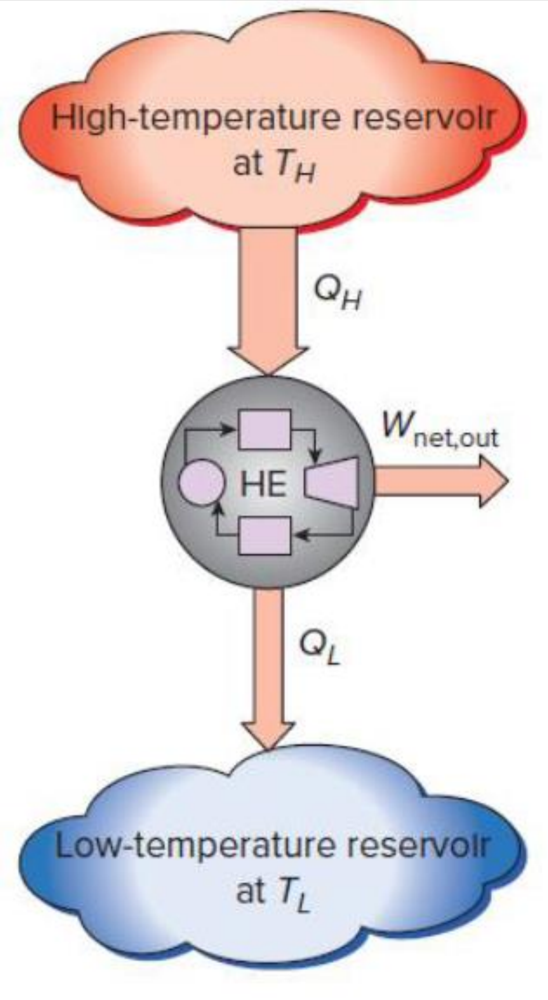


FIGURE 7-13

Schematic of a heat engine.

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_{in}}$$

$$W_{\text{net,out}} = Q_{\text{in}} - Q_{\text{out}}$$

$$\eta_{\text{th}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}}$$

$$W_{\text{net,out}} = Q_H - Q_L$$

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_{in}}$$

$$\eta_{\text{th}} = 1 - \frac{Q_L}{Q_H}$$

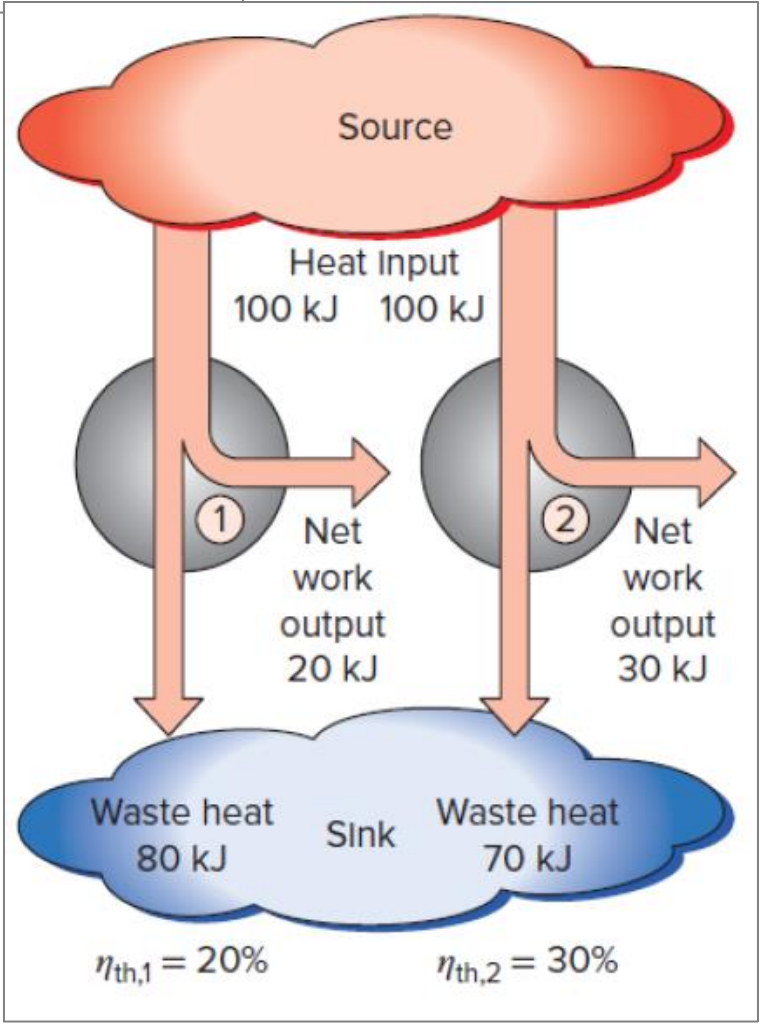


FIGURE 7-12

Some heat engines perform better than others (convert more for the heat they receive to work).

Thermal efficiency-1

$$W_{\text{net,out}} = Q_H - Q_L$$

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_H} \quad \textbf{or} \quad \eta_{\text{th}} = 1 - \frac{Q_L}{Q_H}$$

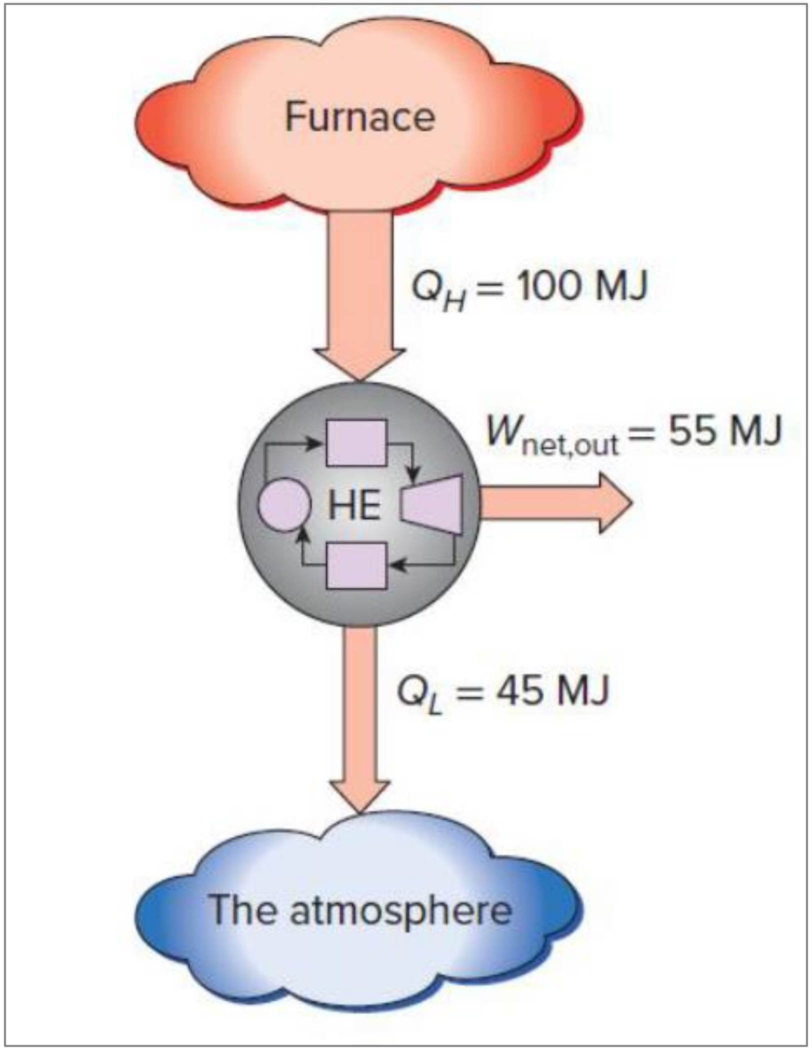


FIGURE 7-14

Even the most efficient heat engines reject almost one-half of the energy they receive as waste heat.

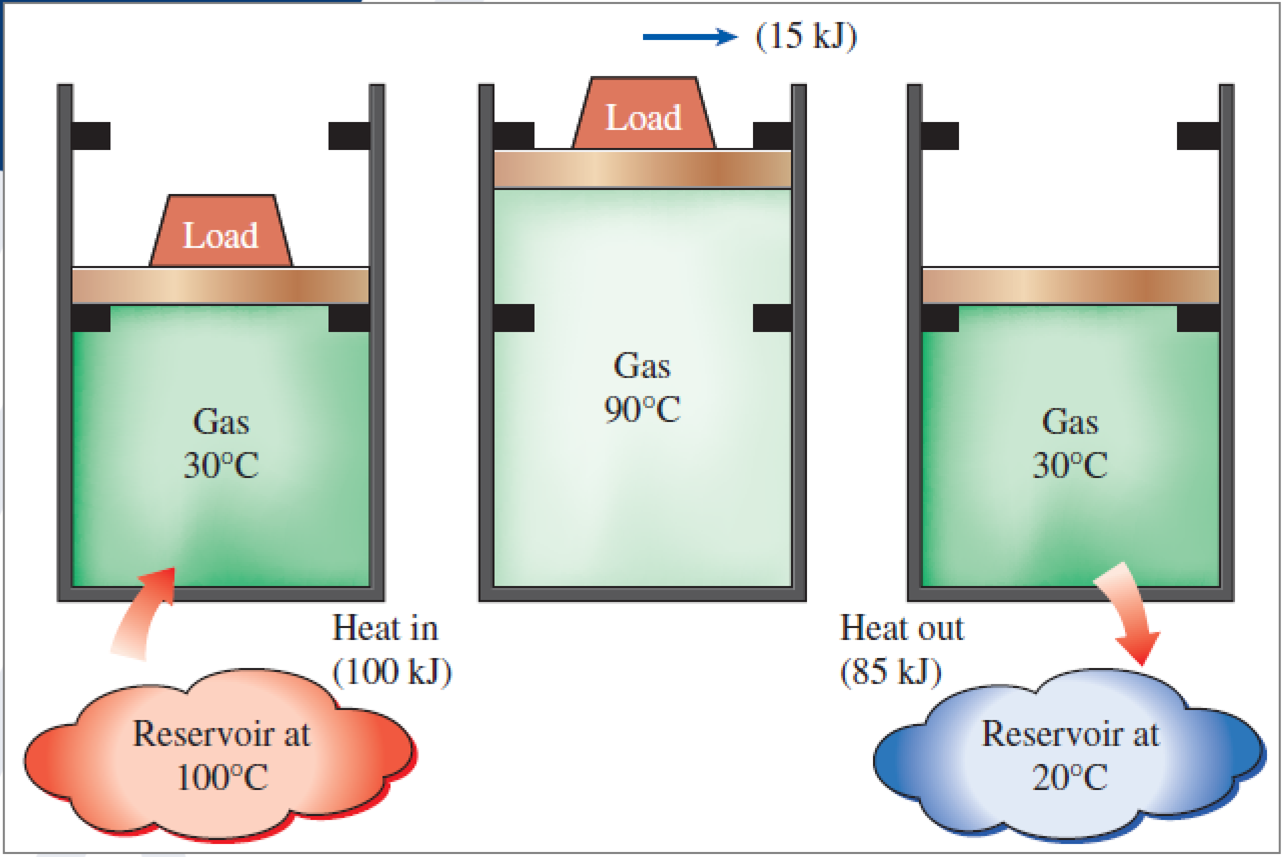


FIGURE 7-15

A heat-engine cycle cannot be completed without rejecting some heat to a low-temperature sink.

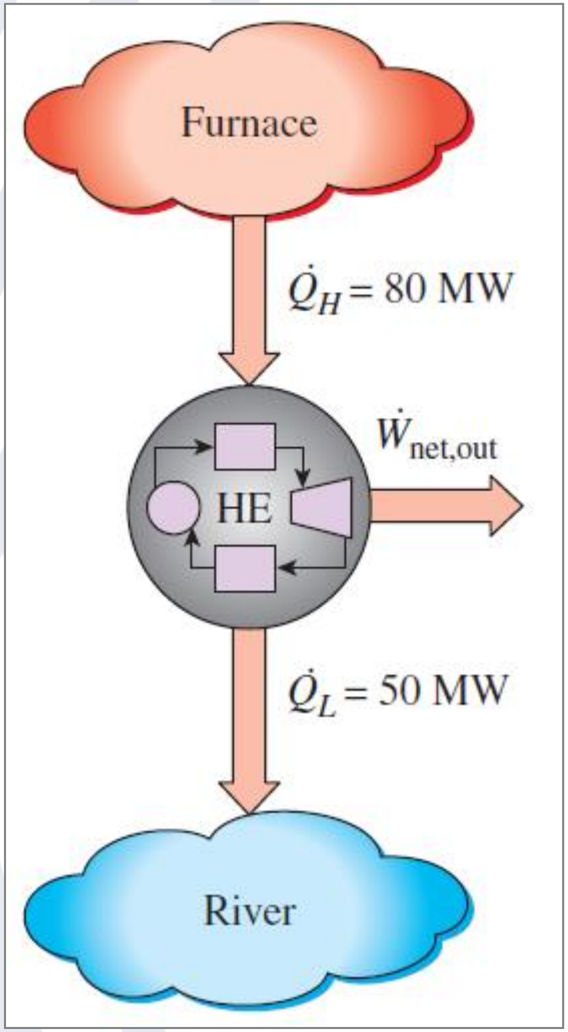
Every heat engine must *waste* some energy by transferring it to a low-temperature reservoir in order to complete the cycle, even under idealized conditions.

Can we save Q_{out}?

In a steam power plant, the condenser is the device where large quantities of waste heat is rejected to rivers, lakes, or the atmosphere.

Can we not just take the condenser out of the plant and save all that waste energy?

The answer is, unfortunately, a firm *no* for the simple reason that without a heat rejection process in a condenser, the cycle cannot be completed.



Net Power Production of a Heat Engine

$$\dot{W}_{\text{net,out}} = \dot{Q}_H - \dot{Q}_L = (80 - 50)\text{ MW} = \mathbf{30\ MW}$$

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{Q}_H} = \frac{30\text{ MW}}{80\text{ MW}} = \mathbf{0.375}(\text{or } 37.5\%)$$

The Second Law of Thermodynamics: Kelvin–Planck Statement

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work. This implies that it is impossible to build a heat engine that has 100% thermal efficiency

***No heat engine can have a thermal efficiency of 100 percent*, or as *for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace*.**

The impossibility of having a 100% efficient heat engine is not due to friction or other dissipative effects. It is a limitation that applies to both the idealized and the actual heat engines.

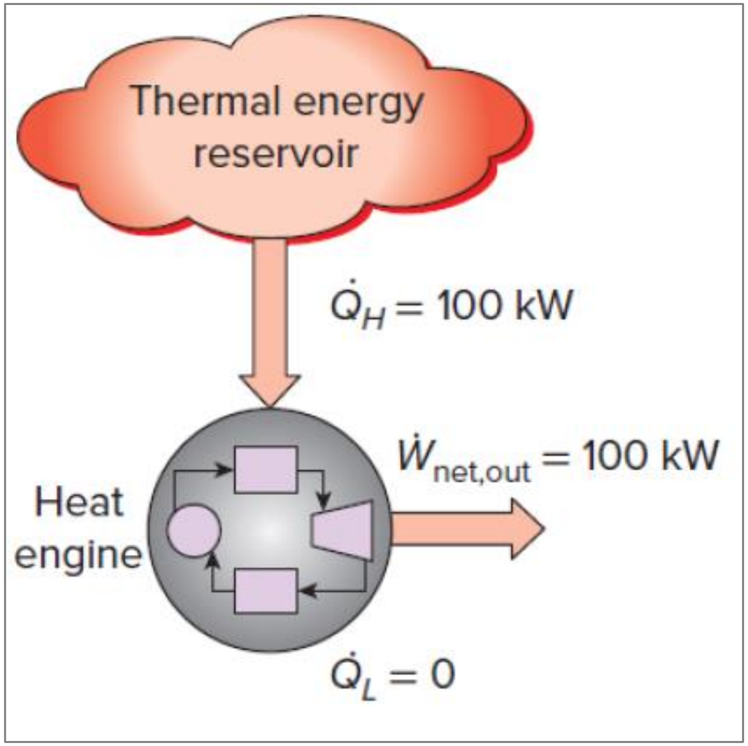


FIGURE 7-18

A heat engine that violates the Kelvin-Planck statement of the second law.

The **Kelvin–Planck statement** (or the Heat Engine **Statement**) of the second law of thermodynamics states that it is impossible to devise a cyclically operating heat engine, the effect of which is to absorb energy in the form of heat from a single thermal reservoir and to deliver an equivalent amount of work.

The Kelvin-Planck statement is the statement of the second law of thermodynamics for heat engines, while the Clausius statement is **the statement of the refrigerators and heat pumps**.

7-4 REFRIGERATORS AND HEAT PUMPS

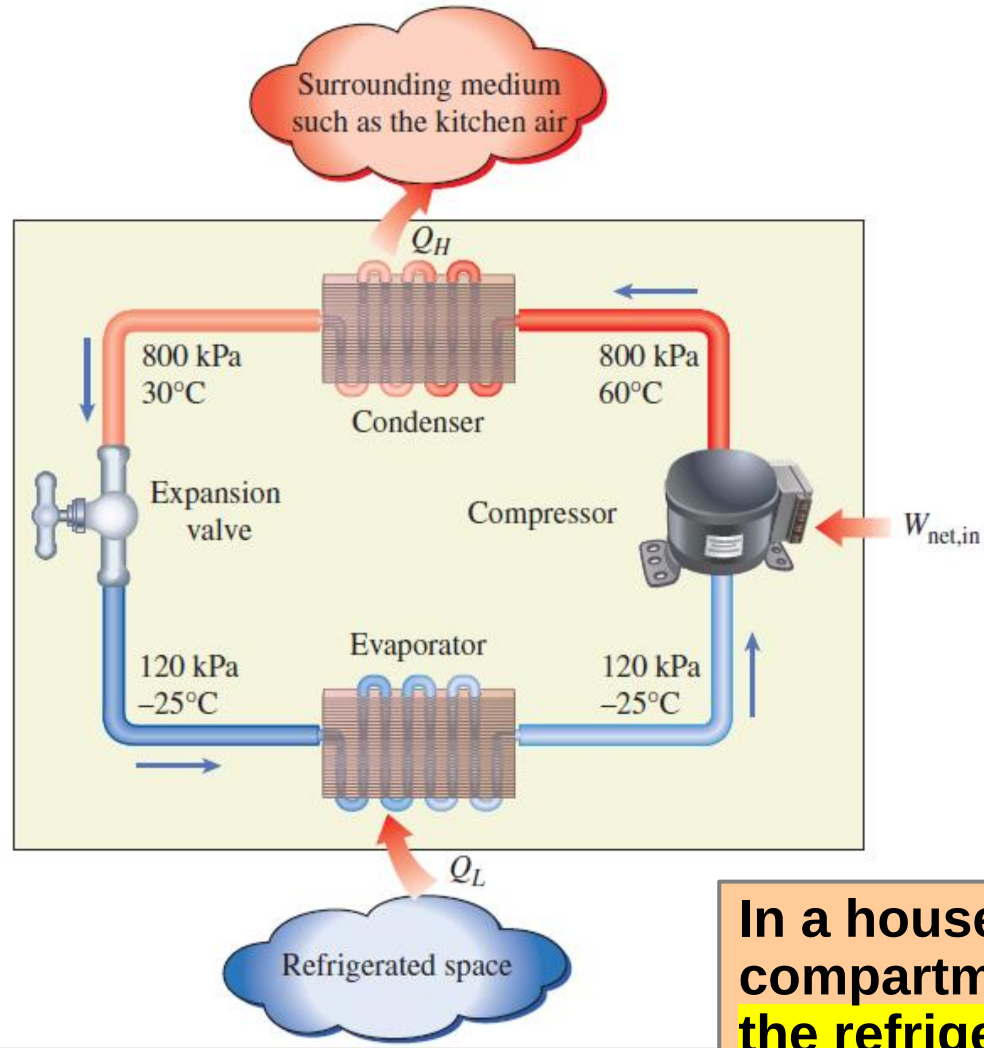


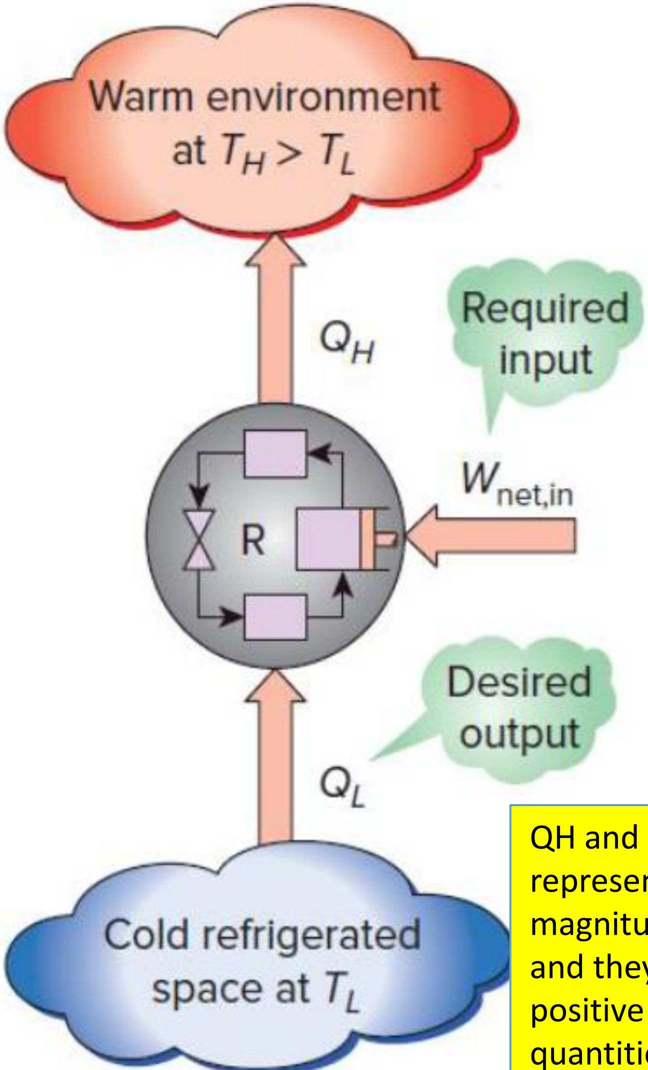
FIGURE 7-19

Basic components of a refrigeration system and typical operating conditions.

- **The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called refrigerators.**
- **Refrigerators, like heat engines, are cyclic devices.**
- **The working fluid used in the refrigeration cycle is called a refrigerant.**
- **The most frequently used refrigeration cycle is the *vapor-compression refrigeration cycle*.**

In a household refrigerator, the freezer compartment where heat is absorbed by the refrigerant serves as the evaporator, and the coils usually behind the refrigerator where heat is dissipated to the kitchen air serve as the condenser.

Coefficient of Performance



QH and Q L represents magnitudes, and they are positive quantities

FIGURE 7-20

The objective of a refrigerator is to remove Q_L from the cooled space.

The *efficiency* of a refrigerator is expressed in terms of the coefficient of performance (COP).

The objective of a refrigerator is to remove heat (QL) from the refrigerated space.

$$\mathrm{COP_R} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{\mathrm{net,in}}}$$

$$W_{\mathrm{net,in}} = Q_H - Q_L \qquad \mathrm{(kJ)}$$

$$\mathrm{COP_R} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

Can the value of $\mathrm{COP_R}$ be greater than unity?

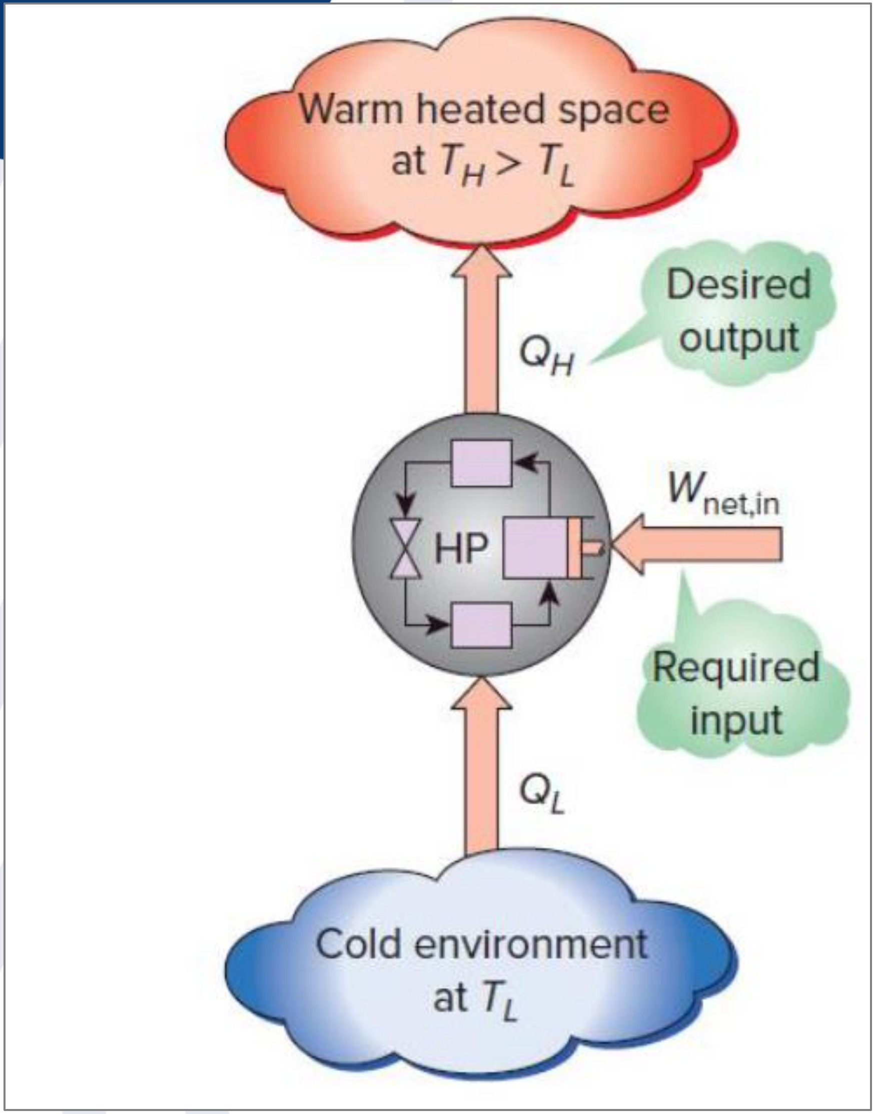


FIGURE 7-21

The objective of a heat pump is to supply heat Q_H into the warmer space.

Heat Pumps

$$\mathrm{COP_{HP}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{\text{net,in}}}$$

$$\mathrm{COP_{HP}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

$$\mathrm{COP_{HP}} = \mathrm{COP_R} + 1$$

for fixed values of Q_L and Q_H

The COP usually exceeds 1, especially in heat pumps, because, instead of just converting work to heat (which, if 100% efficient, would be a COP of 1), **it pumps additional heat from a heat source to where the heat is required**. Most air conditioners have a COP of 2.3 to 3.5.

EXAMPLE 7–1 Net Power Production of a Heat Engine

Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 50 MW, determine the net power output and the thermal efficiency for this heat engine.

SOLUTION

The rates of heat transfer to and from a heat engine are given. The net power output and the thermal efficiency are to be determined.

Assumptions

Heat losses through the pipes and other components are negligible.

Analysis

A schematic of the heat engine is given in **Fig. 7–16**. The furnace serves as the high-temperature reservoir for this heat engine and the river as the low-temperature reservoir. The given quantities can be expressed as

$$\dot{Q}_H = 80 \text{ MW} \quad \text{and} \quad \dot{Q}_L = 50 \text{ MW}$$

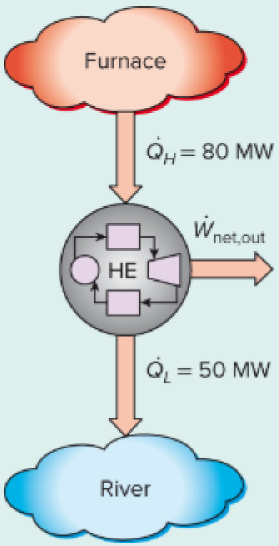


FIGURE 7–16

Schematic for **Example 7–1**.

The net power output of this heat engine is

$$\dot{W}_{\text{net,out}} = \dot{Q}_H - \dot{Q}_L = (80 - 50) \text{ MW} = \mathbf{30 \text{ MW}}$$

Then the thermal efficiency is easily determined to be

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{Q}_H} = \frac{30 \text{ MW}}{80 \text{ MW}} = \mathbf{0.375} \text{ (or 37.5\%)}$$

Discussion

Note that the heat engine converts 37.5 percent of the heat it receives to work.

EXAMPLE 7–2 Fuel Consumption Rate of a Car

A car engine with a power output of 65 hp has a thermal efficiency of 24 percent. Determine the fuel consumption rate of this car if the fuel has a heating value of 19,000 Btu/lbm (i.e., 19,000 Btu of energy is released for each lbm of fuel burned).

SOLUTION

The power output and the efficiency of a car engine are given. The rate of fuel consumption of the car is to be determined.

Assumptions

The power output of the car is constant.

Analysis

A schematic of the car engine is given in **Fig. 7–17**. The car engine is powered by converting 24 percent of the chemical energy released during the combustion process to work. The amount of energy input required to produce a power output of 65 hp is determined from the definition of thermal efficiency to be

$$\dot{Q}_H = \frac{\dot{W}_{\text{net,out}}}{\eta_{\text{th}}} = \frac{65\text{ hp}}{0.24}\left(\frac{2545\text{ Btu/h}}{1\text{ hp}}\right) = 689{,}270\text{ Btu/h}$$

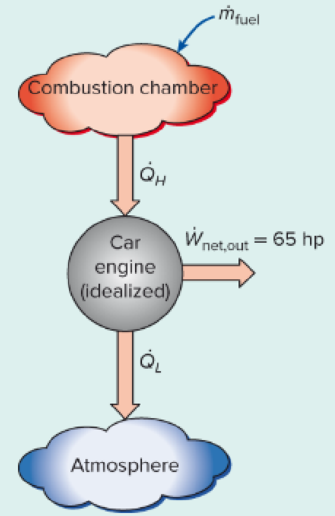


FIGURE 7–17
Schematic for **Example 7–2**.

To supply energy at this rate, the engine must burn fuel at a rate of

$$\dot{m}_{\text{fuel}} = \frac{689{,}270\text{ Btu/h}}{19{,}000\text{ Btu/lbm}} = \mathbf{36.3\text{ lbm/h}}$$

since 19,000 Btu of thermal energy is released for each lbm of fuel burned.

Discussion

Note that if the thermal efficiency of the car could be doubled, the rate of fuel consumption would be reduced by half.

Heat Pump-1

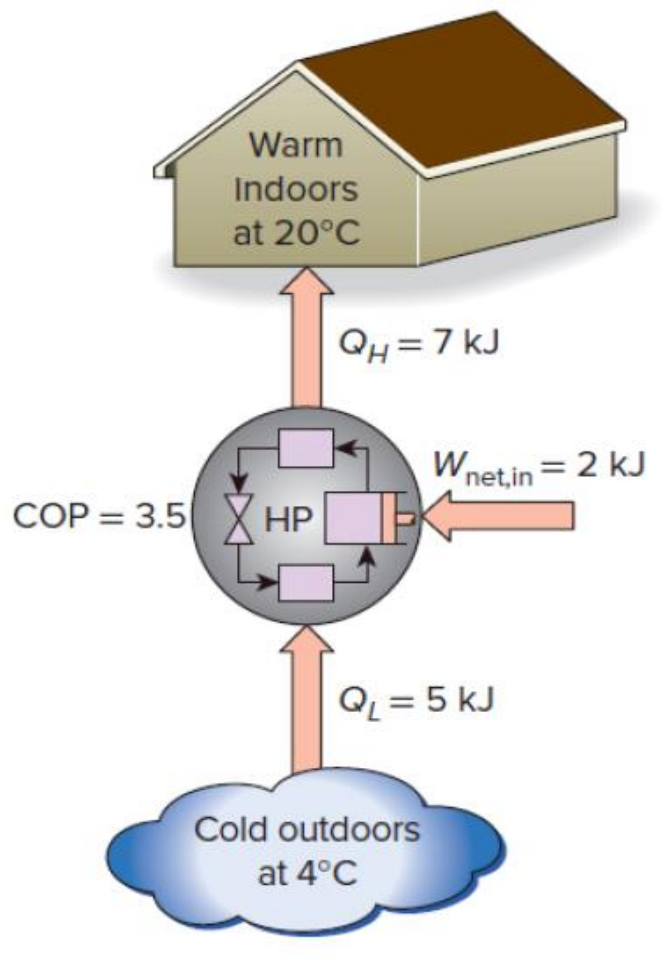


FIGURE 7-22

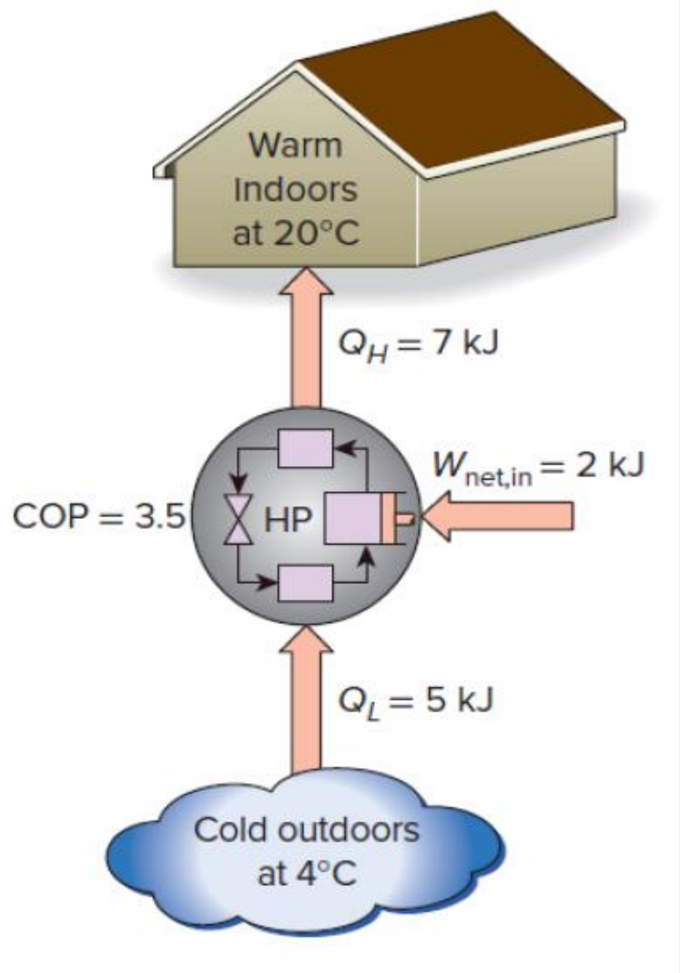
The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors.

- **Most heat pumps in operation today have a seasonally averaged COP of 2 to 3.**
- **Most existing heat pumps use the cold outside air as the heat source in winter (*air-source* HP).**
- **In cold climates their efficiency drops considerably when temperatures are below the freezing point.**
- **In such cases, *geothermal* (*ground-source*) HP that use the ground as the heat source can be used.**

Energy efficiency rating (EER): The amount of heat removed from the cooled space in Btu's for 1 Wh (watthour) of electricity consumed.

$$\text{EER} \equiv 3.412\ \text{COP}_\text{R}$$

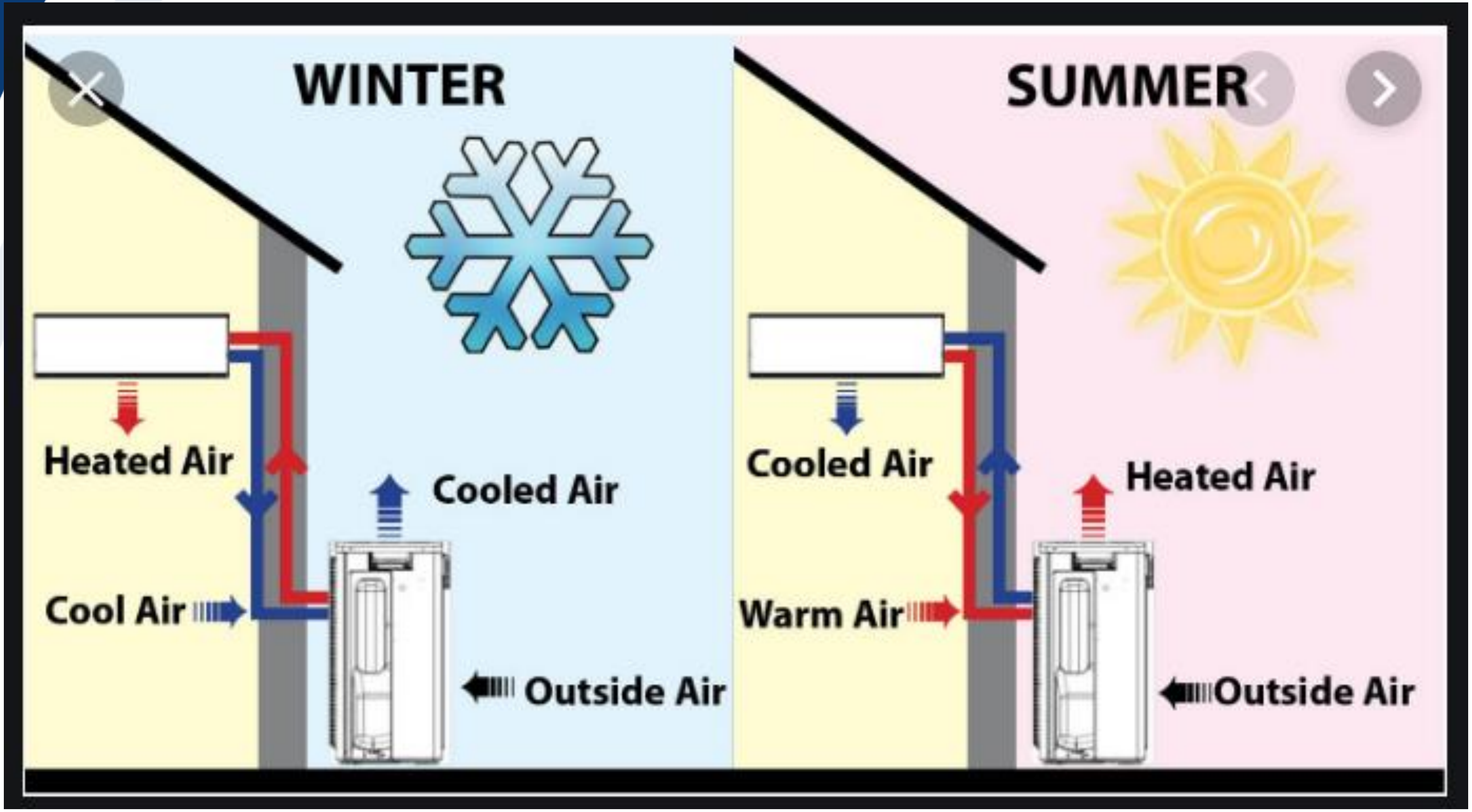
Heat Pump-1



- **Such heat pumps are more expensive to install, but they are also more efficient.**
- **Air conditioners are basically refrigerators whose refrigerated space is a room or a building instead of the food compartment.**
- **The COP of a refrigerator decreases with decreasing refrigeration temperature.**
- **Therefore, it is not economical to refrigerate to a lower temperature than needed.**

FIGURE 7-22

The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors.



A **heat pump** is an electrical device that extracts **heat** from one place and transfers it to another. ... A compressor **pumps** the refrigerant between two **heat** exchanger coils. In one coil, the refrigerant is evaporated at low pressure and absorbs **heat** from its surroundings

EXAMPLE 7–3 Heat Rejection by a Refrigerator

The food compartment of a refrigerator, shown in **Fig. 7–23**, is maintained at 4°C by removing heat from it at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW, determine (*a*) the coefficient of performance of the refrigerator and (*b*) the rate of heat rejection to the room that houses the refrigerator.

SOLUTION

The power consumption of a refrigerator is given. The COP and the rate of heat rejection are to be determined.

Assumptions

Steady operating conditions exist.

Analysis

(*a*) The coefficient of performance of the refrigerator is

$$\mathrm{COP_R} = \frac{\dot{Q}_L}{\dot{W}_{\mathrm{net,in}}} = \frac{360\ \mathrm{kJ/min}}{2\ \mathrm{kW}}\left(\frac{1\ \mathrm{kW}}{60\ \mathrm{kJ/min}}\right) = \mathbf{3}$$

That is, 3 kJ of heat is removed from the refrigerated space for each kJ of work supplied.

(*b*) The rate at which heat is rejected to the room that houses the refrigerator is determined from the conservation of energy relation for cyclic devices,

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{\mathrm{net,in}} = 360\ \mathrm{kJ/min} + (2\ \mathrm{kW})\left(\frac{60\ \mathrm{kJ/min}}{1\ \mathrm{kW}}\right) = \mathbf{480\ kJ/min}$$

Discussion

Notice that both the energy removed from the refrigerated space as heat and the energy supplied to the refrigerator as electrical work eventually show up in the room air and become part of the internal energy of the air. This demonstrates that energy can change from one form to another, can move from one place to another, but is never destroyed during a process.

EXAMPLE 7–4 Heating a House by a Heat Pump

A heat pump is used to meet the heating requirements of a house and maintain it at 20°C. On a day when the outdoor air temperature drops to –2°C, the house is estimated to lose heat at a rate of 80,000 kJ/h. If the heat pump under these conditions has a COP of 2.5, determine (*a*) the power consumed by the heat pump and (*b*) the rate at which heat is absorbed from the cold outdoor air.

SOLUTION

The COP of a heat pump is given. The power consumption and the rate of heat absorption are to be determined.

Assumptions

Steady operating conditions exist.

Analysis

(*a*) The power consumed by this heat pump, shown in **Fig. 7–24**, is determined from the definition of the coefficient of performance to be

$$\dot{W}_{\text{net,in}} = \frac{\dot{Q}_H}{\text{COP}_{\text{HP}}} = \frac{80{,}000 \text{ kJ/h}}{2.5} = \mathbf{32{,}000 \text{ kJ/h}} \text{ (or 8.9 kW)}$$

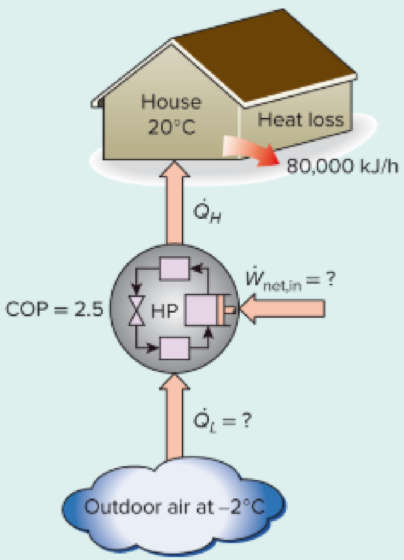


FIGURE 7–24

FIGURE 7–24
Schematic for **Example 7–4**.

(*b*) The house is losing heat at a rate of 80,000 kJ/h. If the house is to be maintained at a constant temperature of 20°C, the heat pump must deliver heat to the house at the same rate, that is, at a rate of 80,000 kJ/h. Then the rate of heat transfer from the outdoor becomes

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{\text{net,in}} = (80{,}000 - 32{,}000) \text{ kJ/h} = \mathbf{48{,}000 \text{ kJ/h}}$$

Discussion

Note that 48,000 of the 80,000 kJ/h heat delivered to the house is actually extracted from the cold outdoor air. Therefore, we are paying only for the 32,000-kJ/h energy that is supplied as electrical work to the heat pump. If we were to use an electric resistance heater instead, we would have to supply the entire 80,000 kJ/h to the resistance heater as electric energy. This would mean a heating bill that is 2.5 times higher. This explains the popularity of heat pumps as heating systems and why they are preferred to simple electric resistance heaters despite their considerably higher initial cost.

The Second Law of Thermodynamics: Clausius Statement

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

It states that a refrigerator cannot operate unless its compressor is driven by an external power source, such as an electric motor.

This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one.

To date, no experiment has been conducted that contradicts the second law, and this should be taken as sufficient proof of its validity.

Clausius Statement of the Second Law

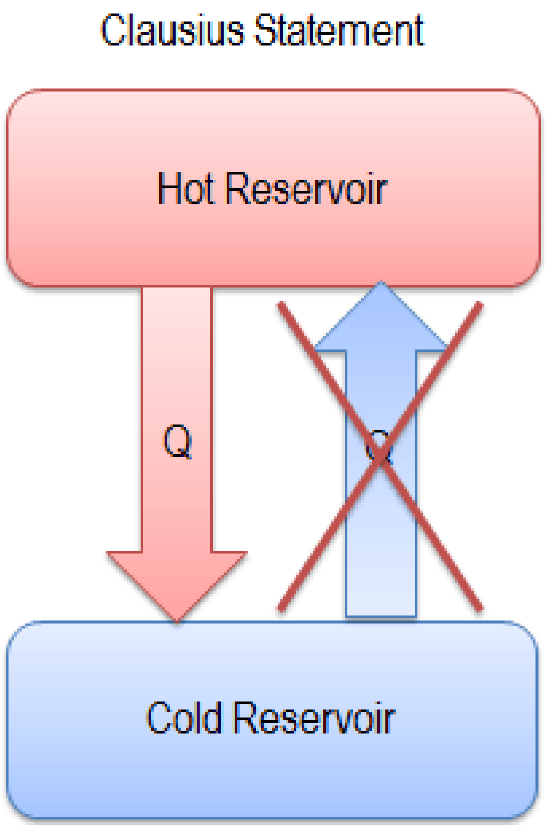
One of the earliest statements of the Second Law of Thermodynamics was made by **R. Clausius in 1850**. He stated the following.

"It is impossible to construct a device which operates on a cycle and whose sole effect is the transfer of heat from a cooler body to a hotter body".

Heat cannot spontaneously flow from cold system to hot system without external work being performed on the system. This is exactly what refrigerators and heat pumps accomplish.

In a refrigerator, heat flows from cold to hot, but only when forced by an external work, refrigerators are driven by electric motors requiring work from their surroundings to operate.

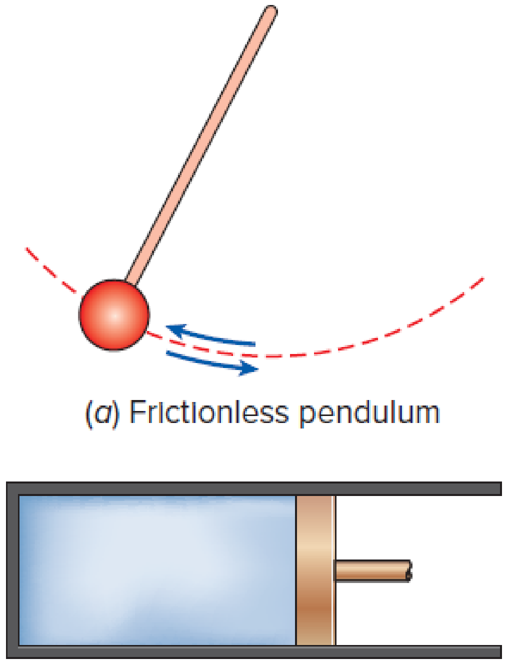
The Clausius and the Kelvin-Planck statements have been shown to be equivalent



7-5 REVERSIBLE AND IRREVERSIBLE PROCESSES

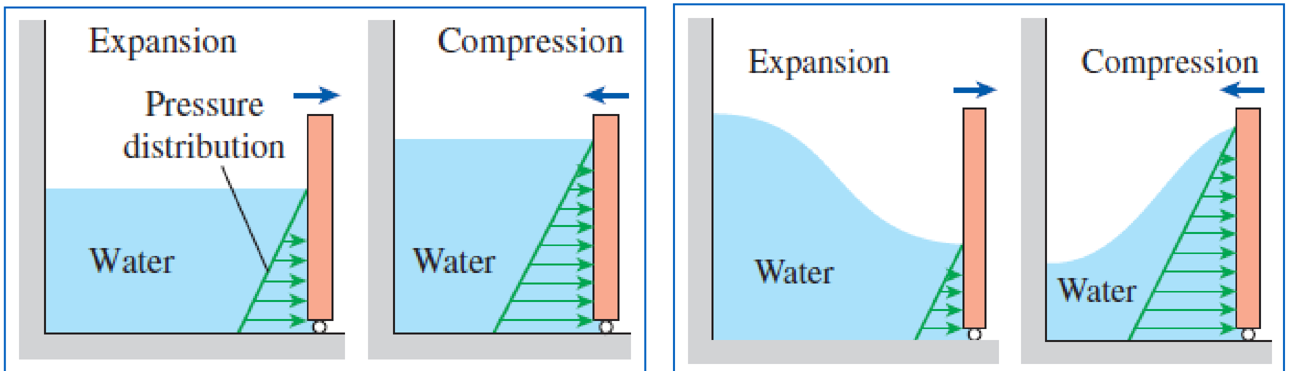
Reversible process: ***A process that can be reversed without leaving any trace on the surroundings.***
Irreversible process: **A process that is not reversible.**

- **All the processes occurring in nature are irreversible.**
- ***Why are we interested*** **in reversible processes?**
- **(1) they are easy to analyze and (2) they serve as idealized models (theoretical limits) to which actual processes can be compared.**
- **Some processes are more irreversible than others.**
- **We try to approximate reversible processes. Why?**



(*a*) Frictionless pendulum

(*b*) Quasi-equilibrium expansion and compression of a gas



(*a*) Slow (reversible) process

(*b*) Fast (irreversible) process

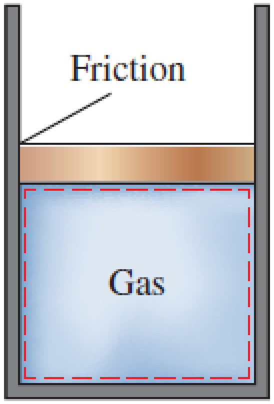
FIGURE 7-27

Two familiar reversible processes.

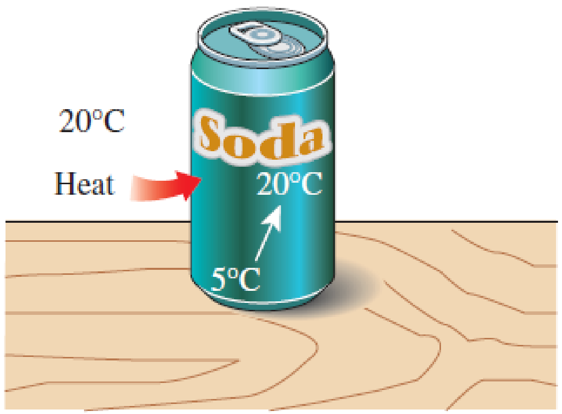
Reversible processes deliver the most and consume the least work.

Irreversibility

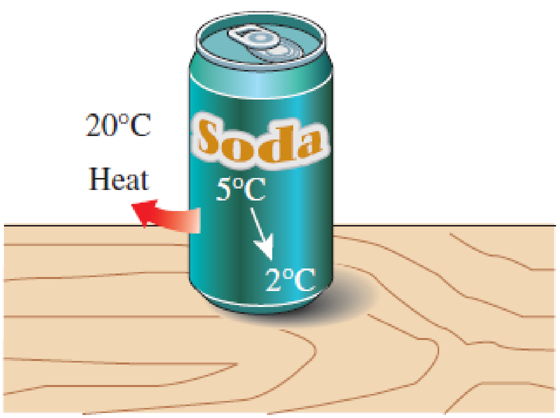
- The factors that cause a process to be irreversible are called **irreversibilities**.
- They include **friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.**
- The presence of any of these effects renders a process irreversible.



Friction renders a process irreversible.

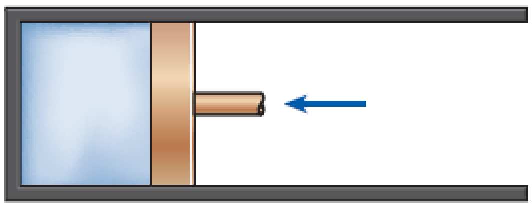


(*a*) An irreversible heat transfer process

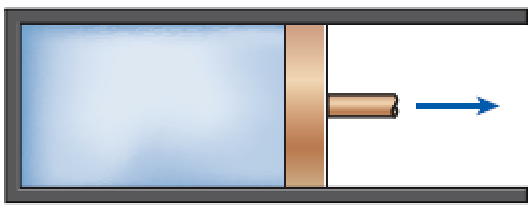


(*b*) An impossible heat transfer process

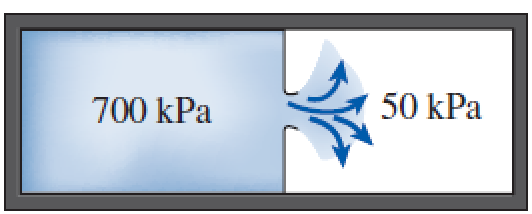
(*a*) Heat transfer through a temperature difference is irreversible, and (*b*) the reverse process is impossible.



(*a*) Fast compression

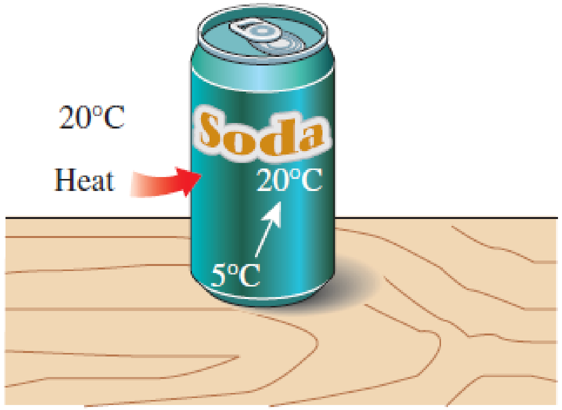


(*b*) Fast expansion

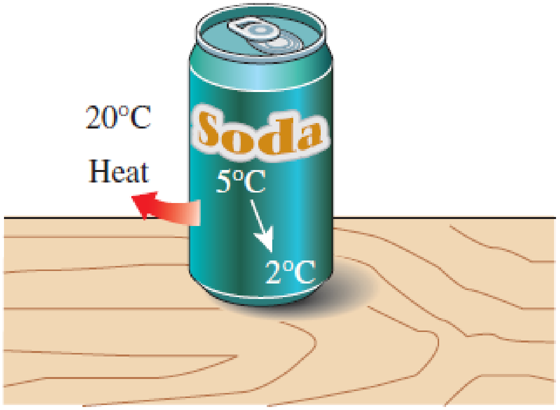


(*c*) Unrestrained expansion

Irreversible compression and expansion processes.



(*a*) An irreversible heat transfer process



(*b*) An impossible heat transfer process

The restoration of the surroundings to the initial state can be done only by converting this excess internal energy completely to work, which is impossible to do without violating the second law.

Since only the system, not both the system and the surroundings, can be restored to its initial condition, heat transfer through a finite temperature difference is an irreversible process

Internally and Externally Reversible Processes

- **Internally reversible process:** If no irreversibilities occur within the boundaries of the system during the process.
- **Externally reversible:** If no irreversibilities occur outside the system boundaries.
- **Totally reversible process:** It involves no irreversibilities within the system or its surroundings.
- A totally reversible process involves no heat transfer through a finite temperature difference, no nonquasi-equilibrium changes, and no friction or other dissipative effects.

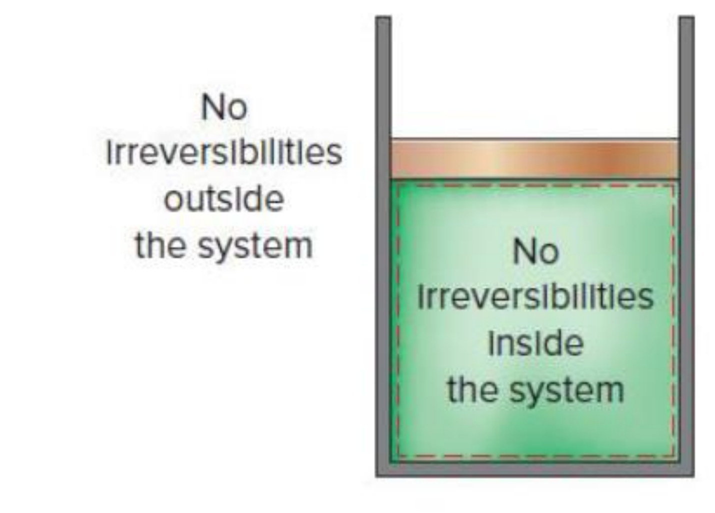


FIGURE 7-32

A reversible process involves no internal and external irreversibilities.

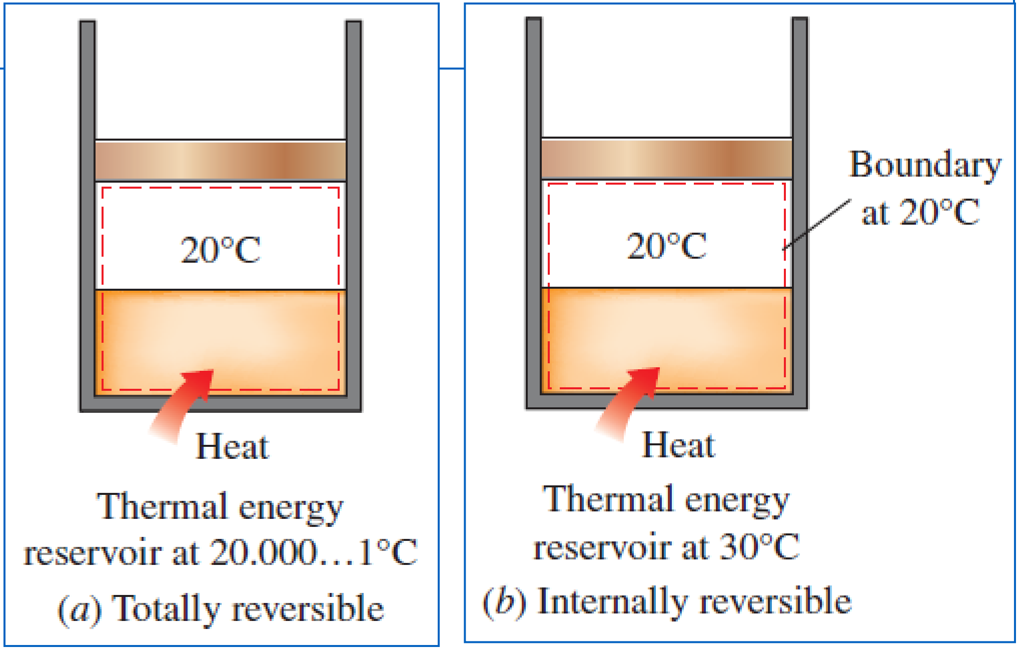
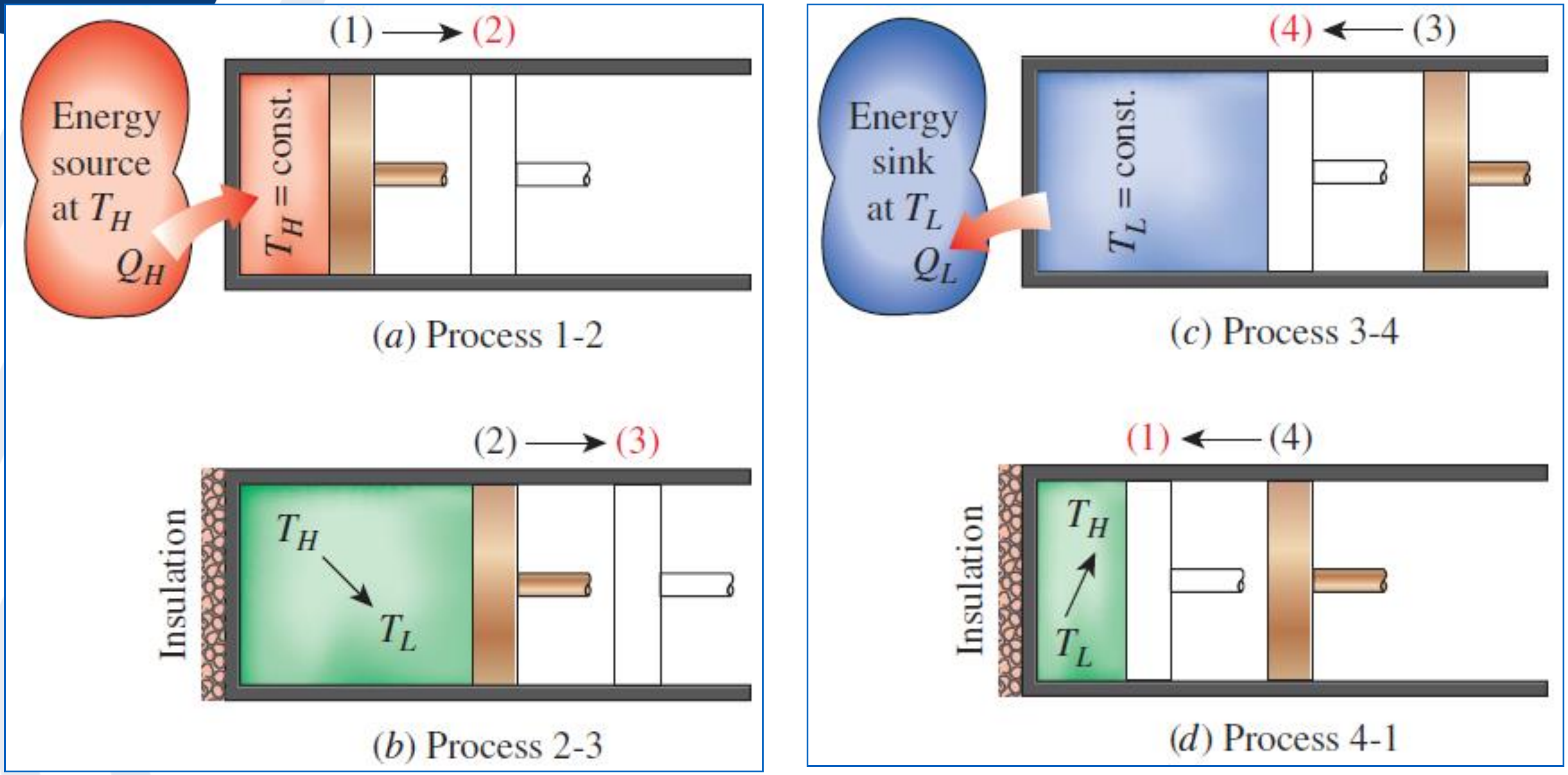


FIGURE 7-33

Totally and internally reversible heat transfer process.

7-6 THE CARNOT CYCLE



Execution of the Carnot cycle in a closed system.

Reversible Isothermal Expansion (process 1-2, $T_H = \text{constant}$**)**
Reversible Adiabatic Expansion (process 2-3, temperature drops from T_H **to** T_L**)**
Reversible Isothermal Compression (process 3-4, $T_L = \text{constant}$**)**
Reversible Adiabatic Compression (process 4-1, temperature rises from T_L **to** T_H**)**

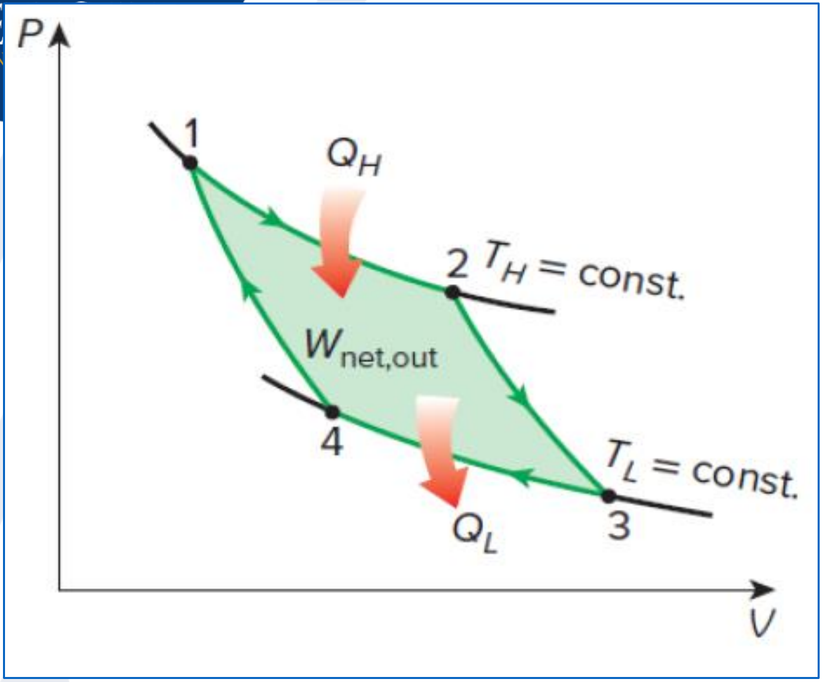


FIGURE 7-35

P-V **diagram of the Carnot cycle.**

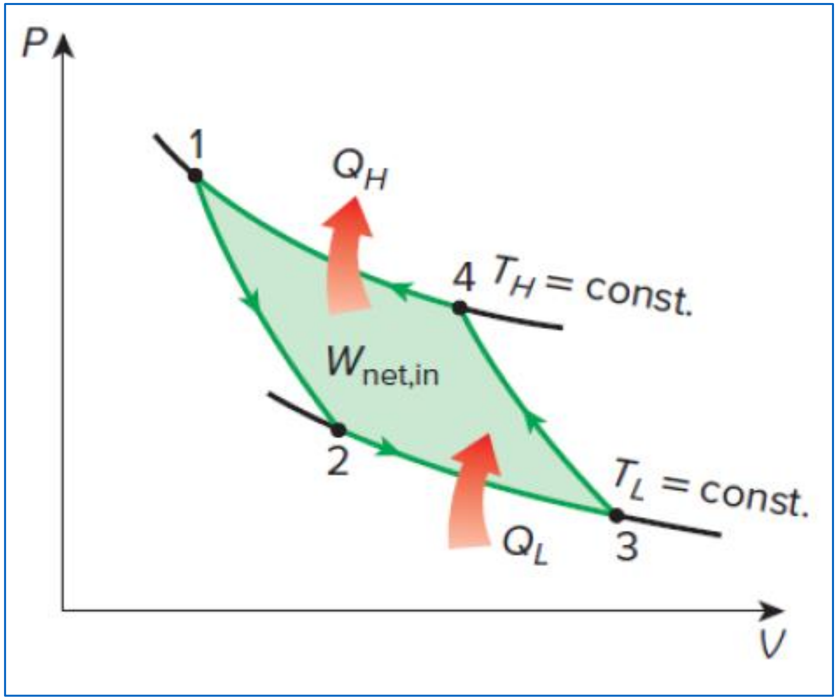


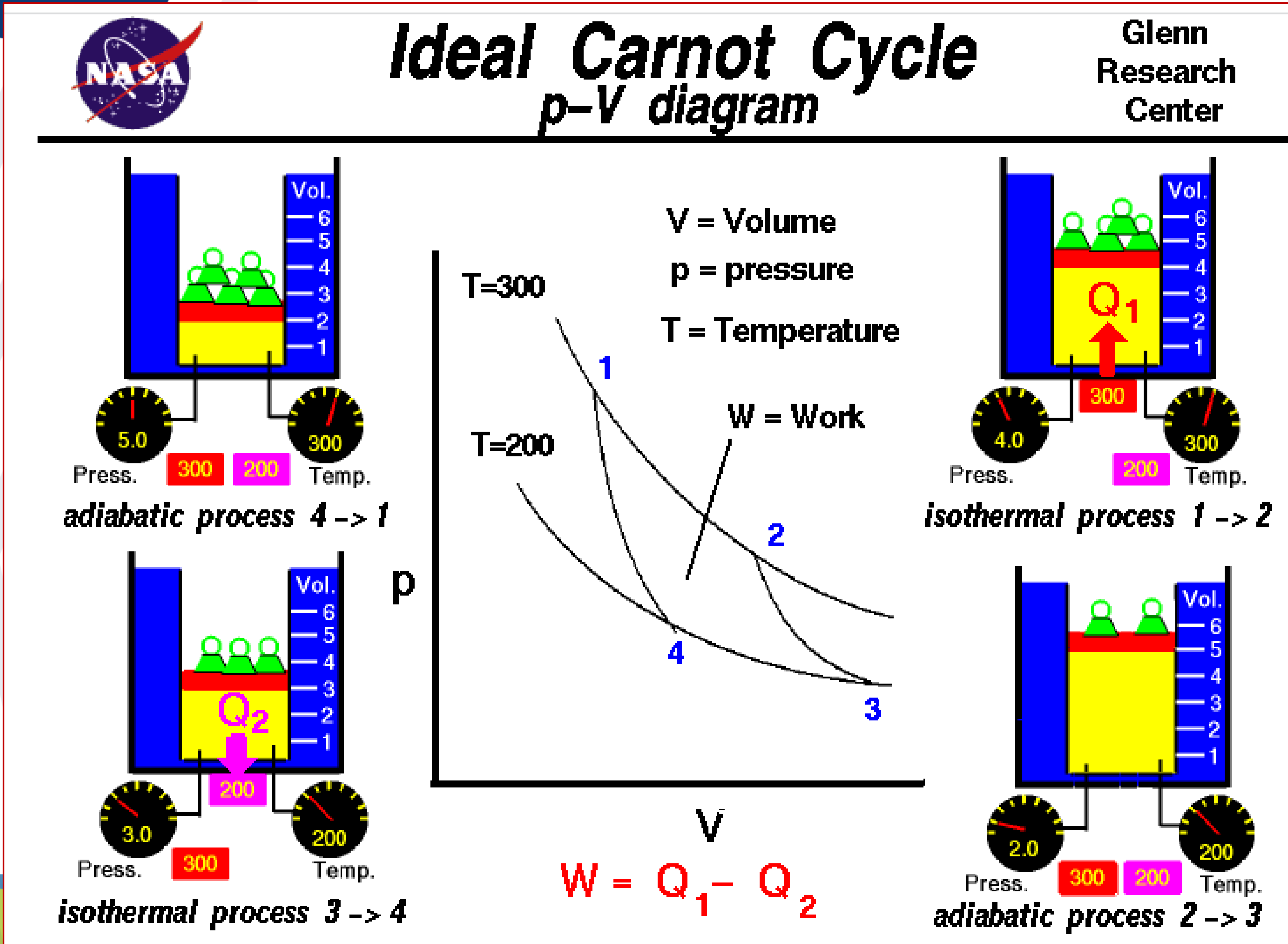
FIGURE 7-36

P-V **diagram of the reversed Carnot cycle.**

The Reversed Carnot Cycle

The Carnot heat-engine cycle is a totally reversible cycle.

Therefore, all the processes that comprise it can be *reversed*, in which case it becomes the Carnot refrigeration cycle.


Ideal Carnot Cycle
p-V diagram
Glenn Research Center
V = Volume
p = pressure
T = Temperature
W = Work
T=300
T=200
1
2
3
4
p
V
Vol.
Press.
Temp.
Q1
Q2
adiabatic process 4 -> 1
isothermal process 1 -> 2
isothermal process 3 -> 4
adiabatic process 2 -> 3
W = Q1 – Q2

- The first process performed on the gas is an **isothermal expansion**. The 300-degree heat source is brought into contact with the cylinder, and weight is removed, which lowers the pressure in the gas. The temperature remains constant, but the volume increases. During the process from **State 1** to **State 2** heat is transferred from the source to the gas to maintain the temperature. We will note the heat transfer by **Q1** into the gas.

- The second process performed on the gas is an **adiabatic expansion**. During an adiabatic process no heat is transferred to the gas. Weight is removed, which lowers the pressure in the gas. The temperature decreases and the volume increases as the gas expands to fill the volume. During the process from **State 2** to **State 3** no heat is transferred.

- The third process performed on the gas is an **isothermal compression**. The 200-degree heat source is brought into contact with the cylinder, and weight is added, which raises the pressure in the gas. The temperature remains constant, but the volume decreases. During the process from **State 3** to **State 4** heat is transferred from the gas to heat source to maintain the temperature. We will note the heat transfer by **Q2** away from the gas.

- The fourth process performed on the gas is an **adiabatic compression**. Weight is added, which raises the pressure in the gas. The temperature increases and the volume decreases as the gas is compressed. During the process from **State 4** to **State 1** no heat is transferred.

7-7 THE CARNOT PRINCIPLES

1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

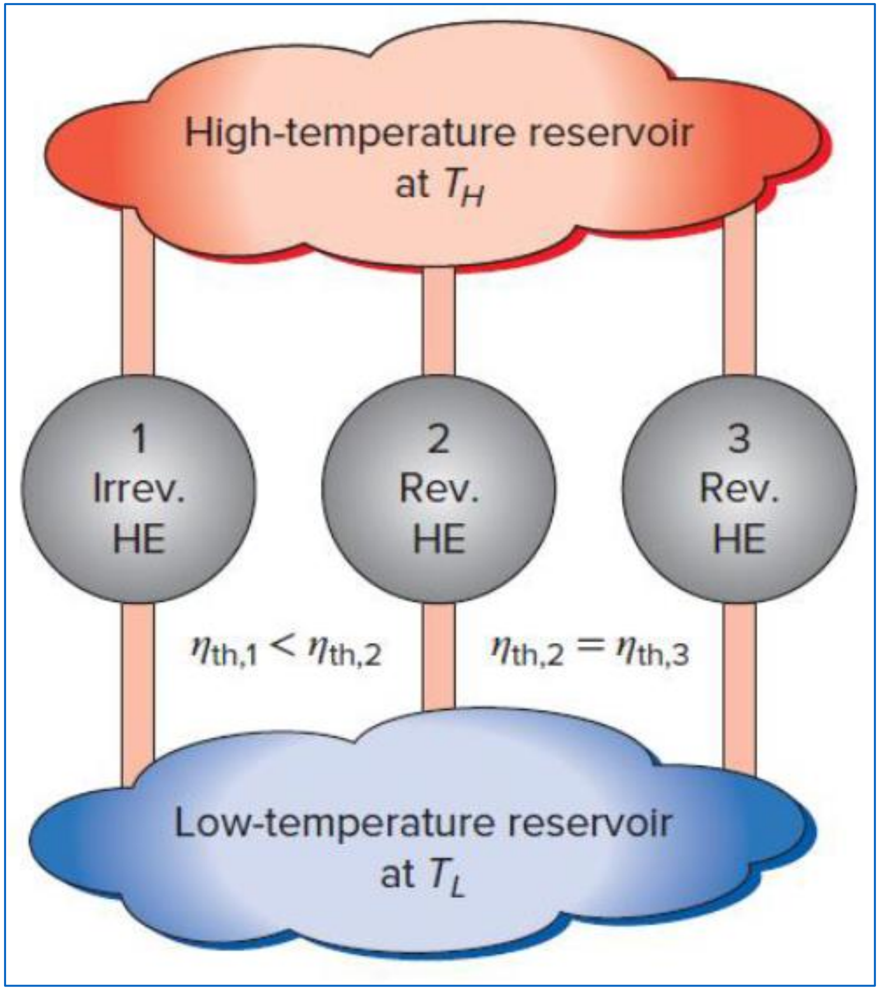
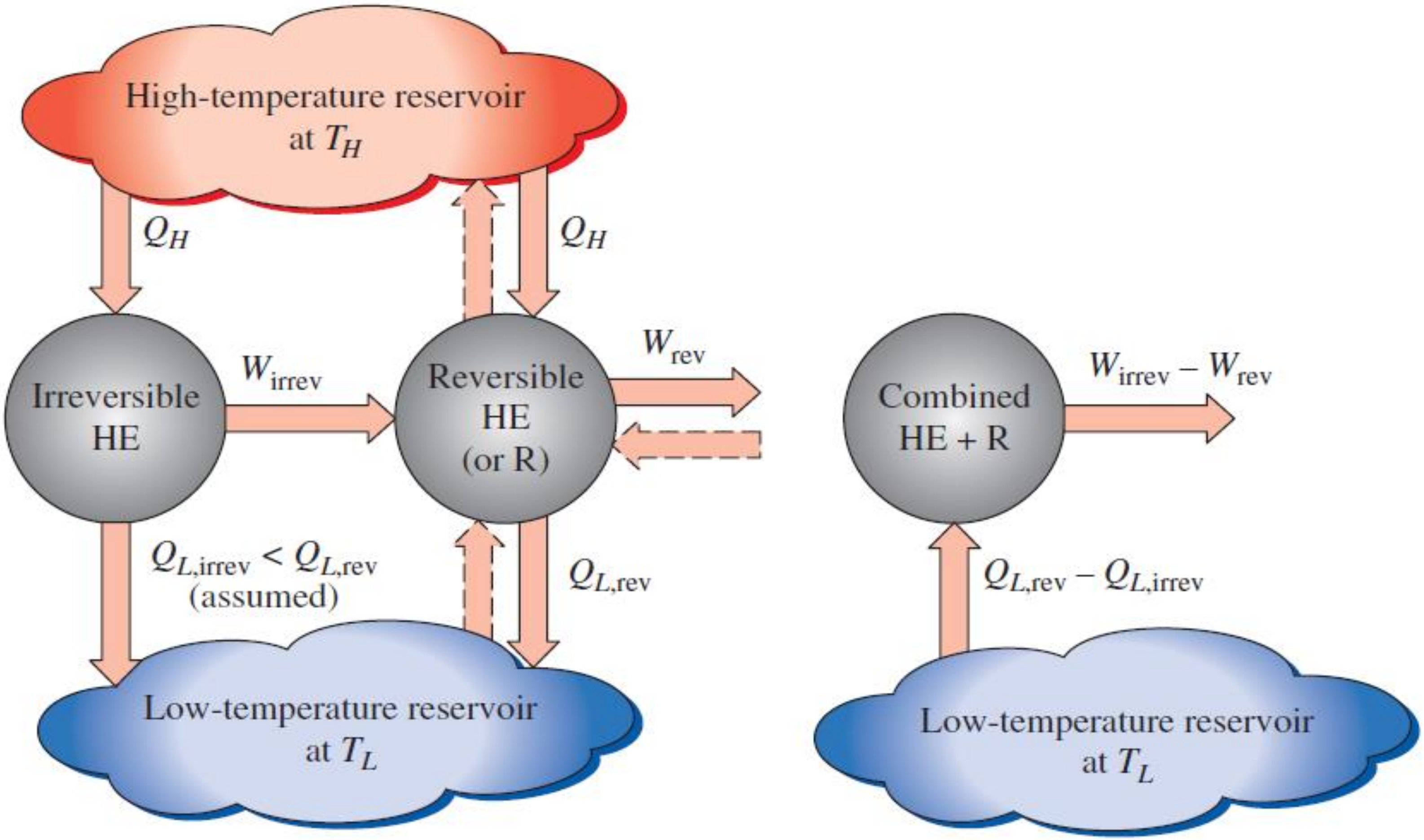


FIGURE 7-37

The Carnot principles.

7-7 THE CARNOT PRINCIPLE-1



(*a*) A reversible and an irreversible heat engine operating between the same two reservoirs (the reversible heat engine is then reversed to run as a refrigerator)

(*b*) The equivalent combined system

FIGURE 7-38

Proof of the first Carnot principle.

7-7 THE CARNOT PRINCIPLE-2

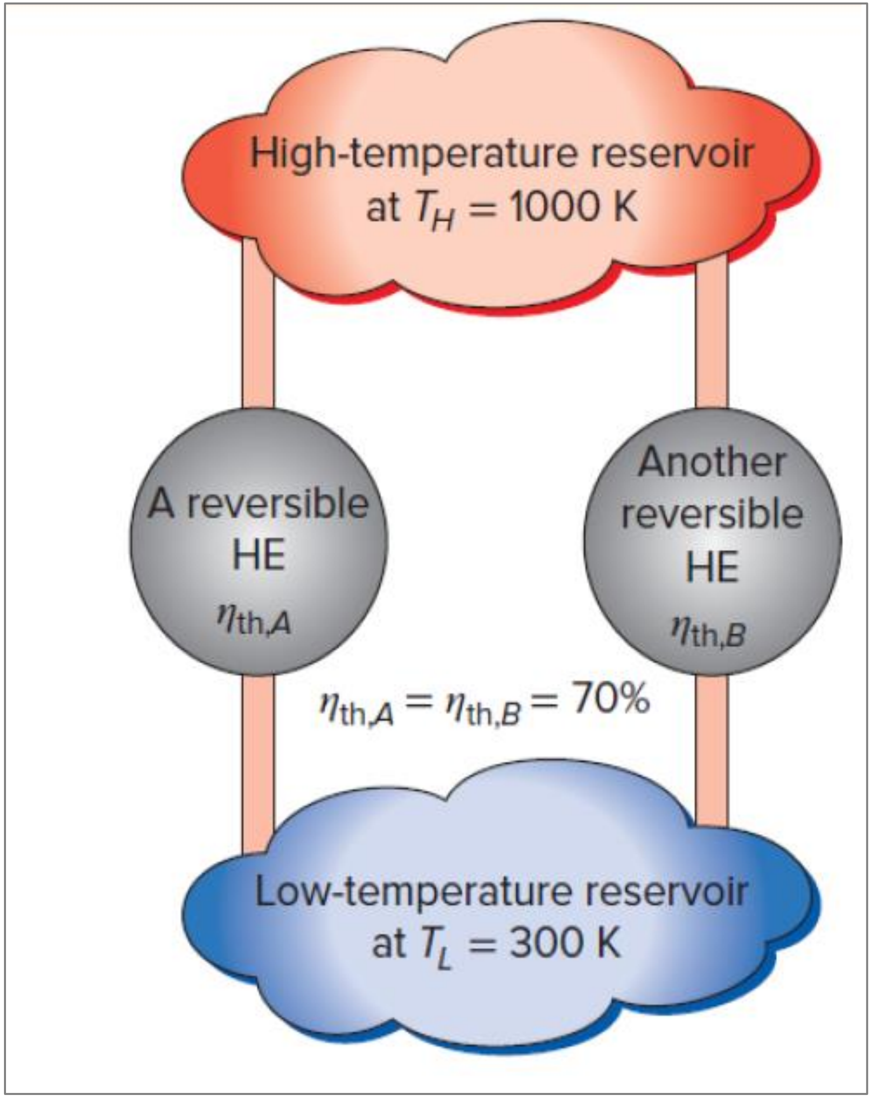


FIGURE 7-39

All reversible heat engines operating between the same two reservoirs have the same efficiency (the second Carnot principle).

EXAMPLE 7–5 Analysis of a Carnot Heat Engine

A Carnot heat engine, shown in **Fig. 7–45**, receives 500 kJ of heat per cycle from a high-temperature source at 652°C and rejects heat to a low-temperature sink at 30°C. Determine (*a*) the thermal efficiency of this Carnot engine and (*b*) the amount of heat rejected to the sink per cycle.

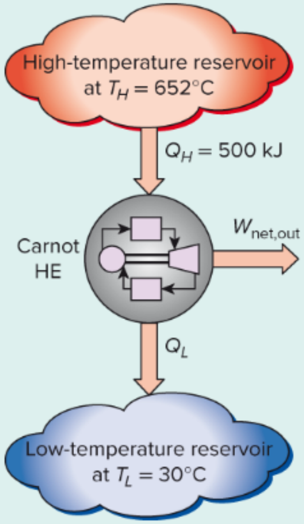


FIGURE 7–45
Schematic for **Example 7–5**.

SOLUTION

The heat supplied to a Carnot heat engine is given. The thermal efficiency and the heat rejected are to be determined.

Analysis

(*a*) The Carnot heat engine is a reversible heat engine, and so its efficiency can be determined from **Eq. 7–18** to be

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{(30 + 273)\ \text{K}}{(652 + 273)\ \text{K}} = \mathbf{0.672}$$

That is, this Carnot heat engine converts 67.2 percent of the heat it receives to work.

(*b*) The amount of heat rejected Q_L by this reversible heat engine is easily determined from **Eq. 7–16** to be

$$Q_{L,rev} = \frac{T_L}{T_H} Q_{H,rev} = \frac{(30 + 273)\ \text{K}}{(652 + 273)\ \text{K}} (500\ \text{kJ}) = \mathbf{164\ kJ}$$

Discussion

Note that this Carnot heat engine rejects to a low-temperature sink 164 kJ of the 500 kJ of heat it receives during each cycle.

EXAMPLE 7–6 **A Carnot Refrigeration Cycle Operating in the Saturation Dome**

A Carnot refrigeration cycle is executed in a closed system in the saturated liquid–vapor mixture region using 0.8 kg of refrigerant-134a as the working fluid (Fig. 7–49). The maximum and the minimum temperatures in the cycle are 20 and –8°C, respectively. It is known that the refrigerant is saturated liquid at the end of the heat rejection process, and the net work input to the cycle is 15 kJ. Determine the fraction of the mass of the refrigerant that vaporizes during the heat addition process, and the pressure at the end of the heat rejection process.

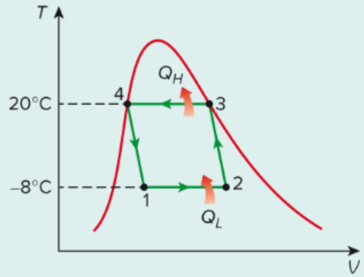


FIGURE 7–49
Schematic for Example 7–6.

SOLUTION

A Carnot refrigeration cycle is executed in a closed system. The mass fraction of the refrigerant that vaporizes during the heat addition process and the pressure at the end of the heat rejection process are to be determined.

Assumptions

The refrigerator operates on the ideal Carnot cycle.

Analysis

Knowing the high and low temperatures, the coefficient of performance of the cycle is

$$\mathrm{COP_R} = \frac{1}{T_H/T_L - 1} = \frac{1}{(20 + 273\ \mathrm{K})/(-8 + 273\ \mathrm{K}) - 1} = 9.464$$

The amount of cooling is determined from the definition of the coefficient of performance to be

$$Q_L = \mathrm{COP_R} \times W_{\mathrm{in}} = (9.464)(15\ \mathrm{kJ}) = 142\ \mathrm{kJ}$$

The enthalpy of vaporization R-134a at −8°C is h_{fg} = 204.59 kJ/kg (Table A-11). Then the amount of refrigerant that vaporizes during heat absorption becomes

$$Q_L = m_{\mathrm{evap}} h_{fg@-8°\mathrm{C}} \rightarrow m_{\mathrm{evap}} = \frac{142\ \mathrm{kJ}}{204.59\ \mathrm{kJ/kg}} = 0.694\ \mathrm{kg}$$

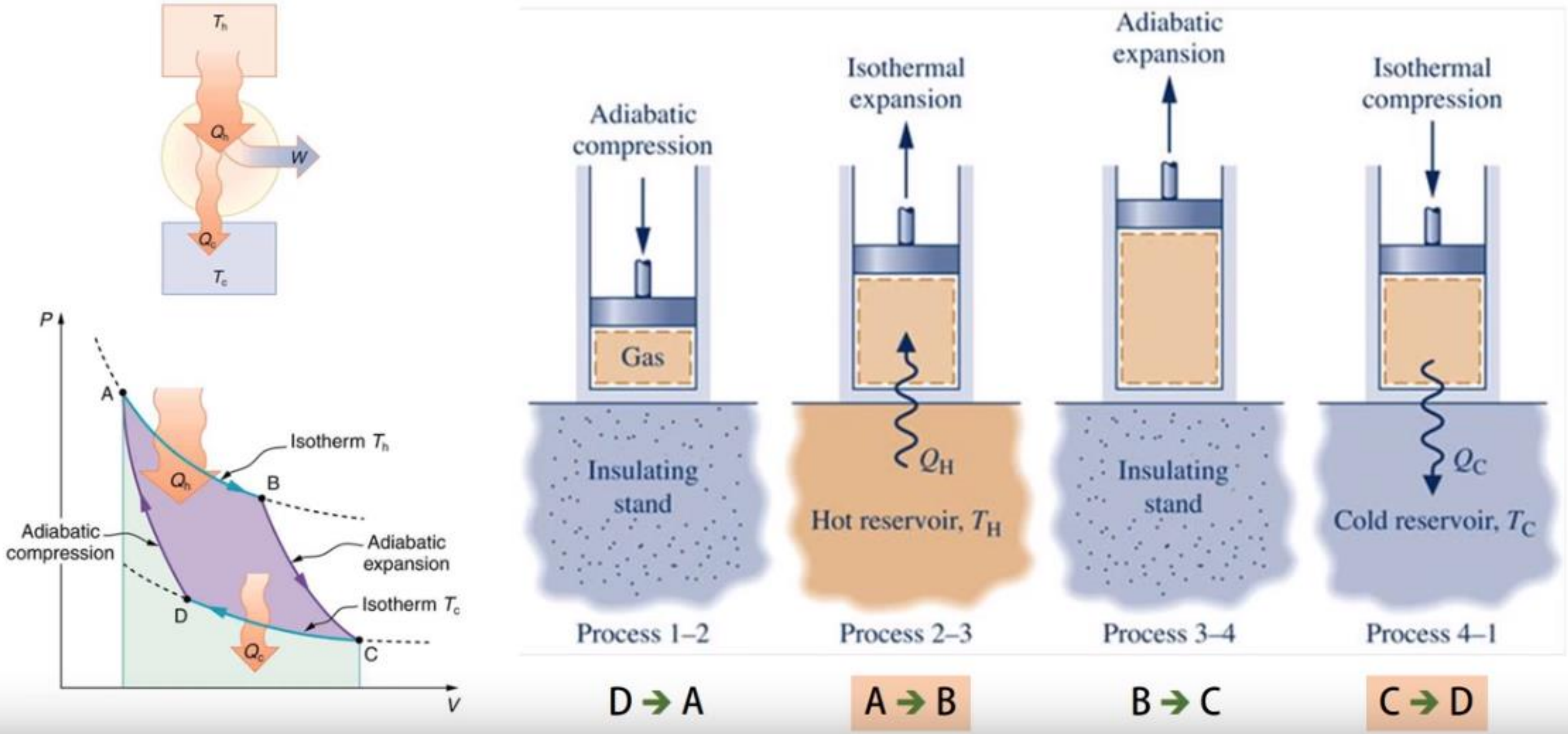
Therefore, the fraction of mass that vaporized during heat addition process to the refrigerant is

$$\text{Mass fraction} = \frac{m_{\mathrm{evap}}}{m_{\mathrm{total}}} = \frac{0.694\ \mathrm{kg}}{0.8\ \mathrm{kg}} = \mathbf{0.868} \text{ or } \mathbf{86.8\%}$$

The pressure at the end of heat rejection process is simply the saturation pressure at heat rejection temperature,

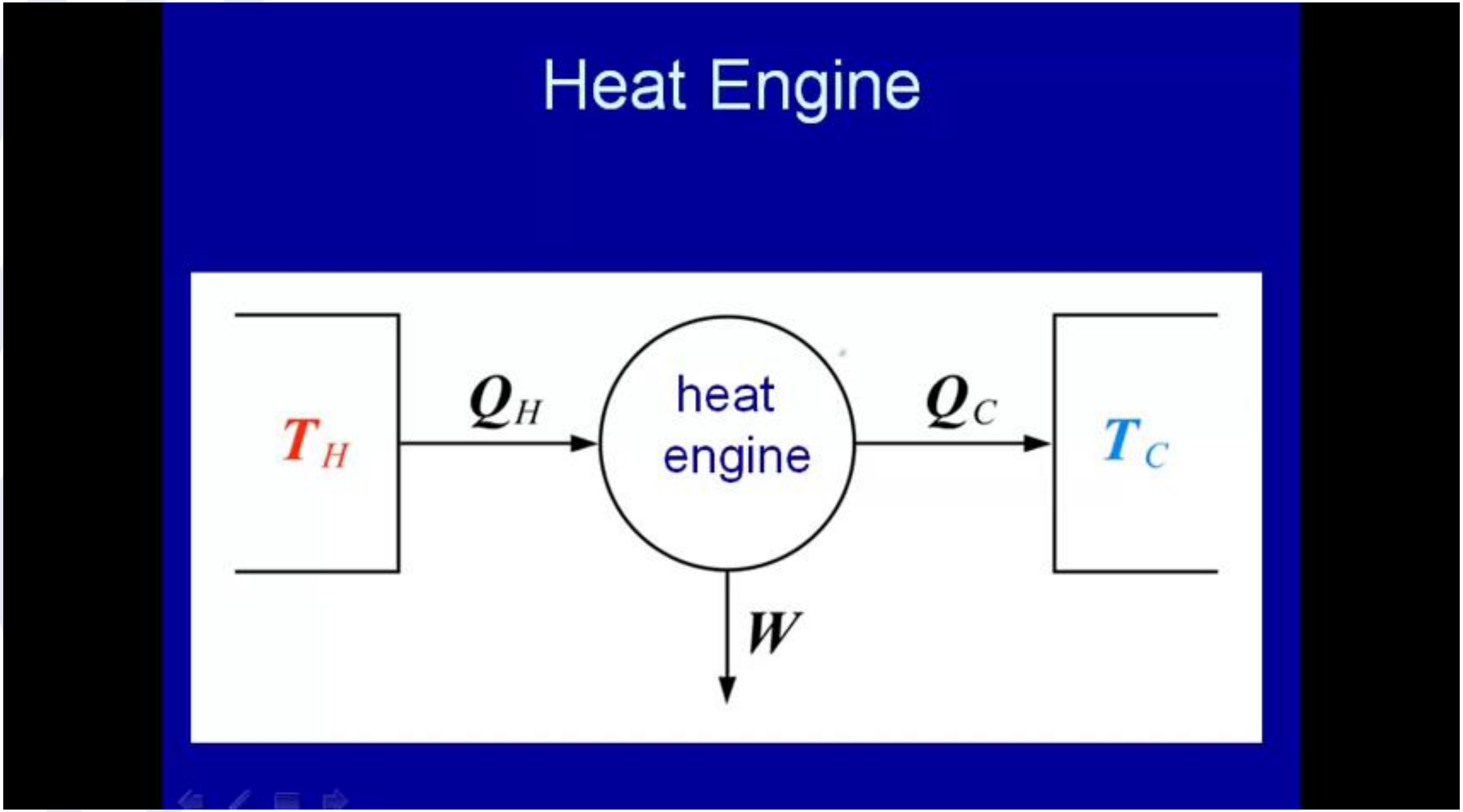
$$P_4 = P_{\mathrm{sat@20°C}} = \mathbf{572.1\ kPa}$$

Carnot Cycle and Heat Engine



youtube.com/watch?v=pRiDJBqVRIw

Carnot Cycle Engine



7-8 THE THERMODYNAMIC TEMPERATURE SCALE

A temperature scale that is independent of the properties of the substances that are used to measure temperature is called a thermodynamic temperature scale.

Such a temperature scale offers great conveniences in thermodynamic calculations.

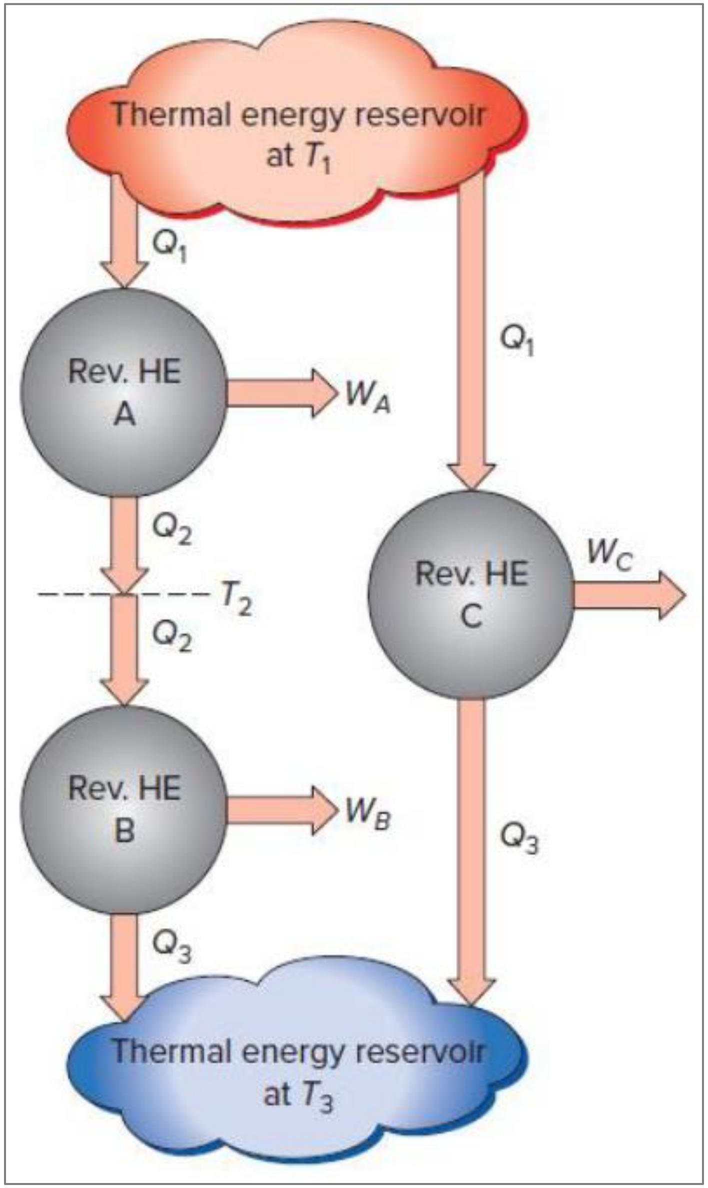


FIGURE 7-40

The arrangement of heat engines used to develop the thermodynamic temperature scale.

7-9 THE CARNOT HEAT ENGINE

$$\eta_{\text{th}} = 1 - \frac{Q_L}{Q_H}$$

Any heat engine

$$\eta_{\text{th,rev}} = 1 - \frac{T_L}{T_H}$$

Carnot heat engine

$$\eta_{\text{th}} \begin{cases} < \eta_{\text{th,rev}} & \text{irreversible heat engine} \\ = \eta_{\text{th,rev}} & \text{reversible heat engine} \\ > \eta_{\text{th,rev}} & \text{impossible heat engine} \end{cases}$$

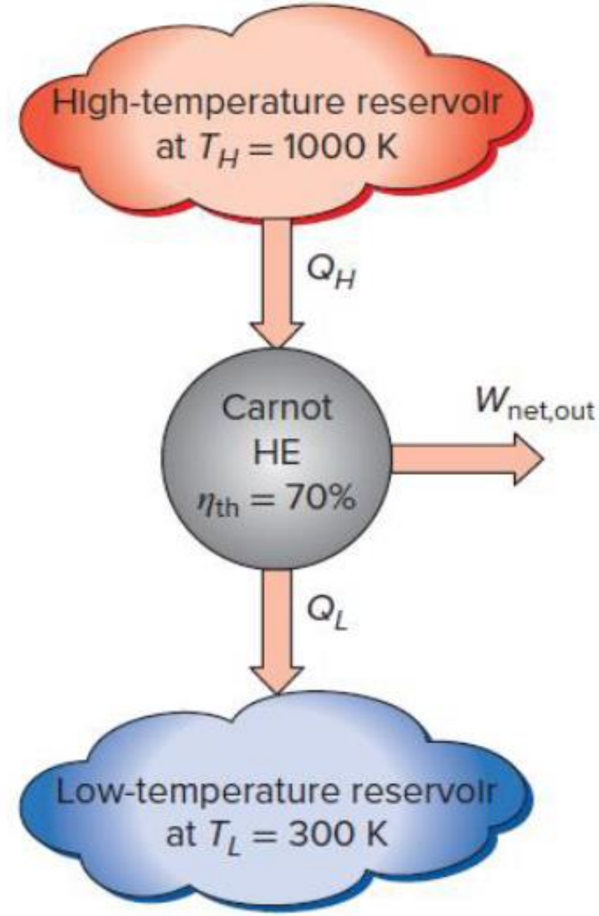


FIGURE 7-43

The Carnot heat engine is the most efficient of all heat engines operating between the same high-and low-temperature reservoirs.

7-9 THE CARNOT HEAT ENGINE-1

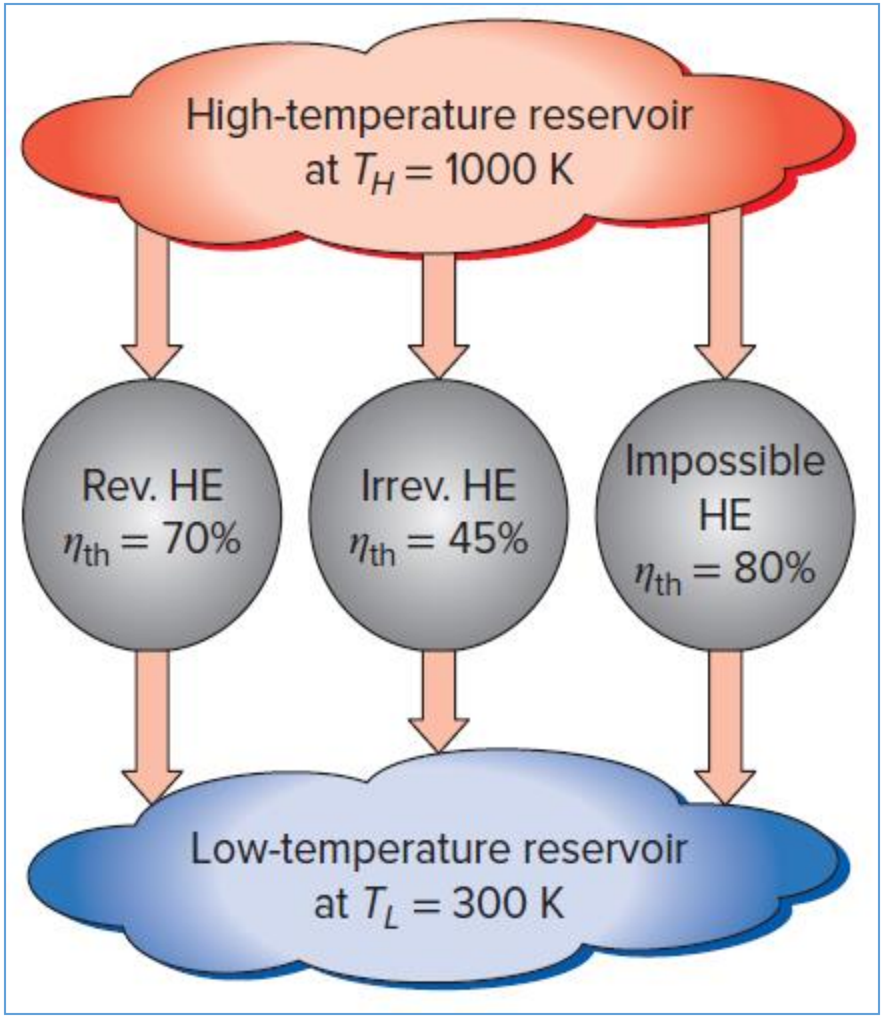
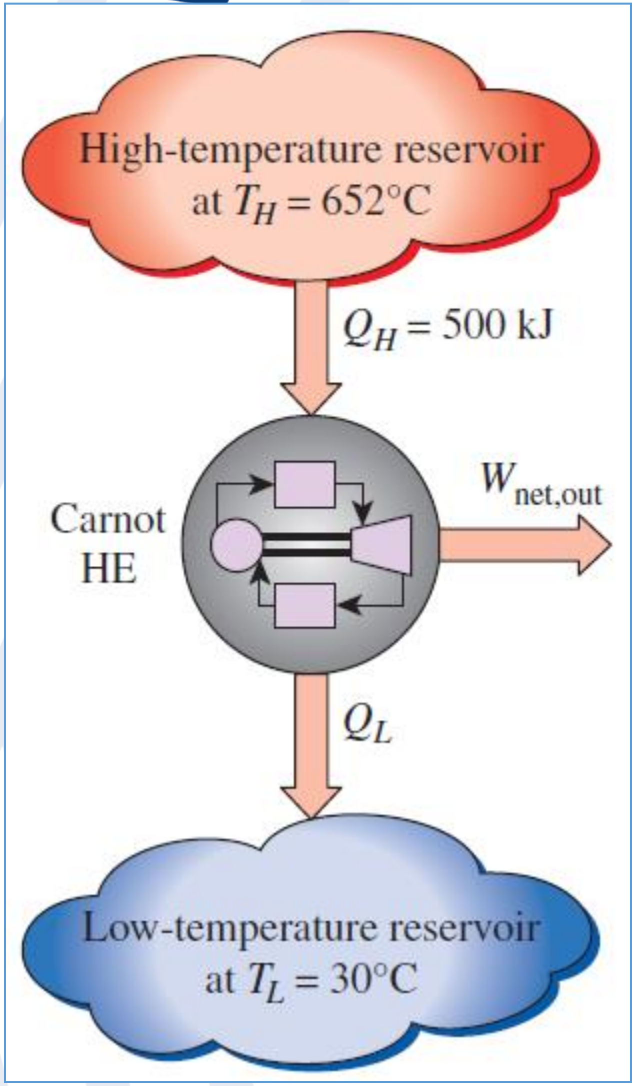


FIGURE 7-44

No heat engine can have a higher efficiency than a reversible heat engine operating between the same high-and low-temperature reservoirs.

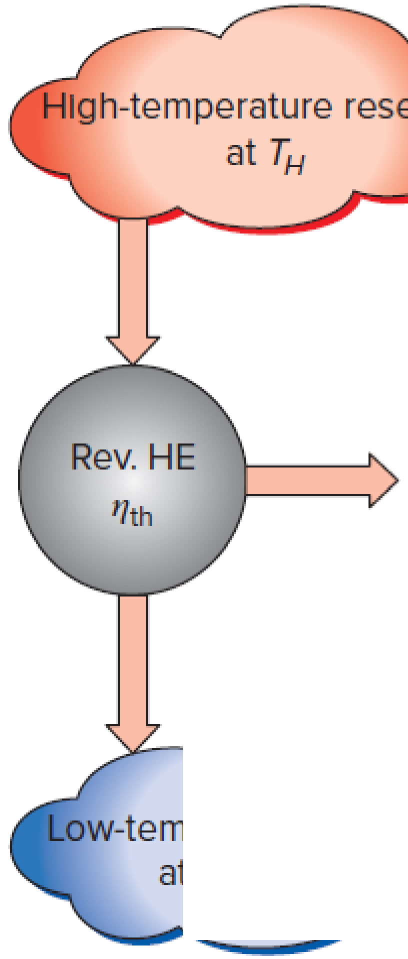
Analysis of a Carnot Heat Engine



$$\eta_{th,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{(30 + 273)\text{K}}{(652 + 273)\text{K}} = \mathbf{0.672}$$

$$Q_{L,rev} = \frac{T_L}{T_H} Q_{H,rev} = \frac{(30 + 273)\text{K}}{(652 + 273)\text{K}} (500\ \text{kJ}) = \mathbf{164\ kJ}$$

The Quality of Energy



T_H, K	η_{th}, %
925	67.2
800	62.1
700	56.7
500	39.4
350	13.4

FIGURE 7-46
The fraction of heat that can be con-verted to work as a function of source temperature (for $T_L = 303\text{K}$).

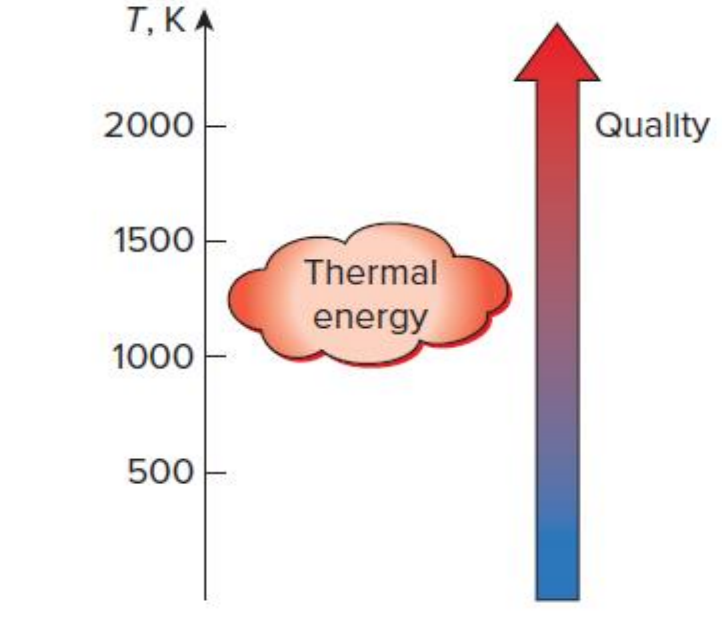


FIGURE 7-47
The higher the temperature of the thermal energy, the higher its quality.

$$\eta_{\text{th,rev}} = 1 - \frac{T_L}{T_H}$$

Can we use ℃ unit for temperature here?

7-10 THE CARNOT REFRIGERATOR AND HEAT PUMP

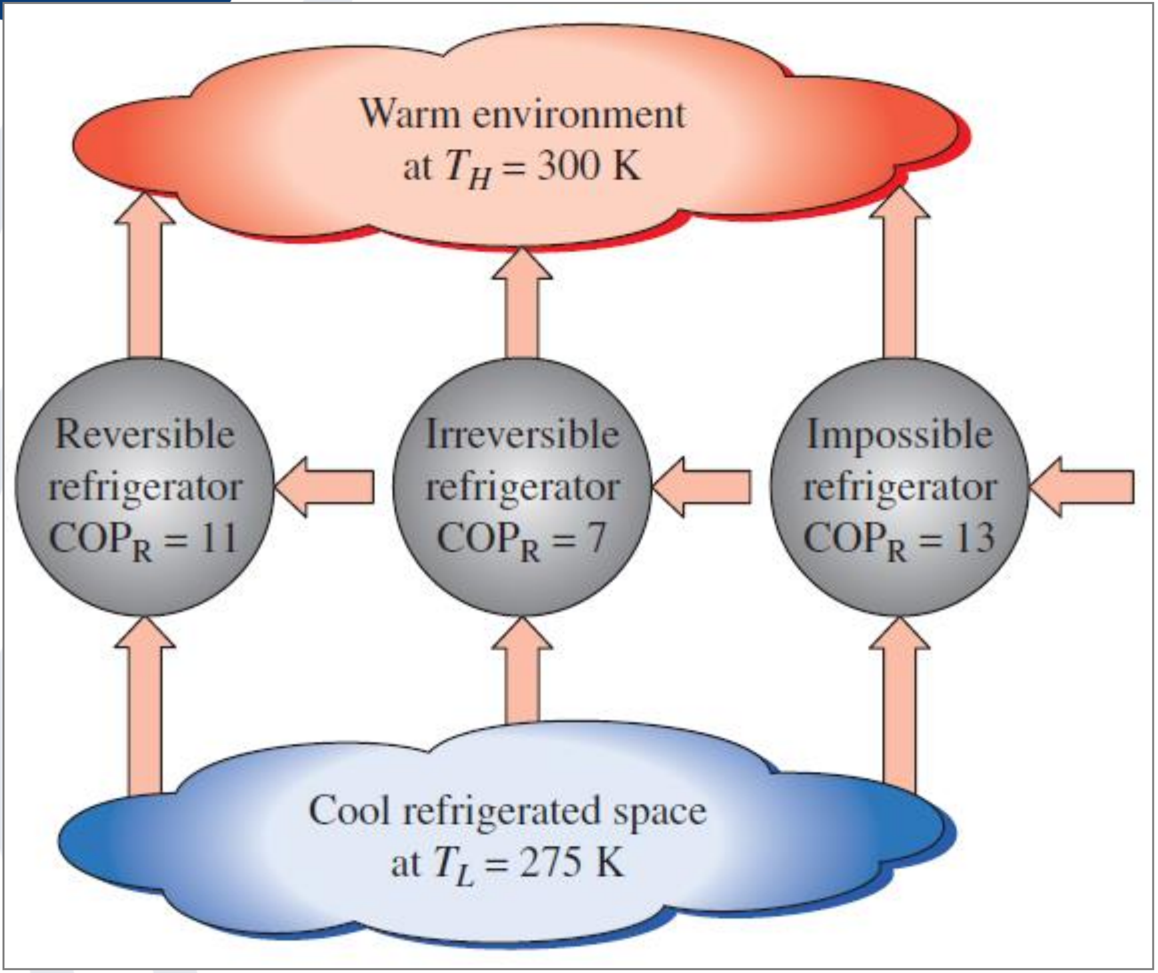


FIGURE 7-48
No refrigerator can have a higher COP than a reversible refrigerator operating between the same temperature limits.

Any refrigerator or heat pump

$$\mathrm{COP_R} = \frac{1}{Q_H/Q_L - 1}$$

$$\mathrm{COP_R} = \frac{1}{1 - Q_L/Q_H}$$

Carnot refrigerator or heat pump

$$\mathrm{COP_{R,rev}} = \frac{1}{T_H/T_L - 1}$$

$$\mathrm{COP_{R,rev}} = \frac{1}{1 - T_L/T_H}$$

7-10 THE CARNOT REFRIGERATOR AND HEAT PUMP-1

$$\mathrm{COP_R} \begin{cases} < \ \mathrm{COP_{R,rev}} & \text{irreversible refrigerator} \\ = \ \mathrm{COP_{R,rev}} & \text{reversible refrigerator} \\ > \ \mathrm{COP_{R,rev}} & \text{impossible refrigerator} \end{cases}$$

The COP of a reversible refrigerator or heat pump is the maximum theoretical value for the specified temperature limits.

Actual refrigerators or heat pumps may approach these values as their designs are improved, but they can never reach them.

The COPs of both the refrigerators and the heat pumps decrease as T_L decreases.

That is, it requires more work to absorb heat from lower-temperature media.

Summary

- **Introduction to the second law**
- **Thermal energy reservoirs**
- **Heat engines**
  - Thermal efficiency
  - The 2nd law: Kelvin-Planck statement
- **Refrigerators and heat pumps**
  - Coefficient of performance (COP)
  - The 2nd law: Clasius statement
- **Reversible and irreversible processes**
  - Irreversibilities, Internally and externally reversible processes
- **The Carnot cycle**
  - The reversed Carnot cycle
- **The Carnot principles**
- **The thermodynamic temperature scale**
- **The Carnot heat engine**
  - The quality of energy
- **The Carnot refrigerator and heat pump**